Cranfield University

Anne Peregrine Dain-Owens

The damaging effect of surface-traffic-generated soil pressures on buried archaeological artefacts

School of Applied Sciences
Natural Resources Department

PhD

Academic year: 2009 – 2010

Supervisors

Professor Mark Kibblewhite
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Abstract

The aim of this work was to investigate the influence of surface loading from conventional field operations on the damage to buried artefacts, both pots and bones.

The objectives of this research were a) to investigate the influence of surface loading and resulting breakage relating to the material strengths of buried objects - ceramic (unglazed), and aged bone; b) to assess the magnitudes of peak subsurface pressures transferred through soil under the dynamic surface loading from tyres and other field operations; c) to develop and test an empirical model for predicting the effects of subsurface pressure application on buried objects from surface loads; and d) to explore ways of identifying the potential for damage to buried artefacts under agricultural and other field operations.

Experimental investigations were performed in both the laboratory and field. The laboratory work was undertaken to determine the magnitude of subsurface pressure at which buried objects were damaged. Conducted in a sandy-loam-filled soil bin, instrumented ceramic and bone artefacts were buried alongside pressure sensors and subjected to loading by a single smooth tyre appropriately loaded and inflated for subsurface pressure generation. The breakage of the buried objects and the pressures under the moving tyre were recorded in order to allow correlation of the subsurface pressures to buried artefact breakage. The fieldwork was done to determine the magnitudes of subsurface pressure generated by individual field operations whilst travelling in a similar sandy loam field soil. Four plots were established, with each assigned a particular cultivation regime. An accelerated timeframe was utilized so that a years' series of field operations could be driven over pressure sensors buried in the soil. The peak pressures from each field operation within each plot were recorded and summarized, and the data was analysed relative to field operation type and cultivation regime type.

Multiple statistical analyses were performed, as the laboratory data and field data were independently evaluated before being correlated together. An empirical relationship between buried object damage and subsurface pressure magnitude was developed.

The different pot types and bone orientations broke at different subsurface pressures. The four pot types listed in ascending order of strength to resist damage (with breakage pressure threshold value) are: shell tempered (1.3 bar), grog tempered (1.6 bar), flint tempered (3.1 bar), and sand tempered (3.6 bar). Aged human radius bones were tested, and the parallel bone orientation proved stronger than the perpendicular orientation, where 2.8 bar was the lowest subsurface pressure found to cause damage.

The primary field operations, presented in ascending order relative to peak magnitude of subsurface pressure per specific operation, are: roll (0.68 bar), drill (1.03 bar), heavy duty cultivator (1.21 bar), spray 1 (1.27 bar), harvester (1.30 bar), spray 2 (1.31 bar), tractor / trailer

(1.46 bar), shallow mouldboard plough (1.61 bar), deep mouldboard plough (2.04 bar). The relationships between vehicle specification and subsurface pressure generation potential were described, relating to the vehicle mass, tyre/track physical properties, and tyre inflation pressure. The effect of cultivation method on overall magnitude of subsurface pressure was defined, with lowest pressure generation within a zero-till cultivation regime (1.08 bar), higher in a non-inversion cultivation regime (1.13 bar), followed by the shallow inversion regime (1.22 bar), and highest within a conventional inversion scheme (1.30 bar).

The laboratory and field results were correlated by a statistical analysis comparing breakage point to peak subsurface pressure. The shell tempered pot was found to be most susceptible to damage. The grog tempered pot was less vulnerable to damage, followed by the flint tempered pot. The quartz tempered pot was predicted to survive intact under all field operations within this research.

In conclusion, this research has developed a functional and predictive empirical relationship between damage to pot and aged bone artefacts from subsurface soil pressures generated by surface traffic.

It has been found that different types of buried pot and bone artefacts break at different subsurface pressures. In addition, a complete dataset consisting of peak subsurface pressures recorded under a year's range of field operations within a sandy loam soil at field-working moisture content has been compiled. The effect of different cultivation methods on the generation of subsurface pressures was also evaluated. The breakage thresholds specific to each artefact type have been related to the in-field subsurface soil pressures. A correlation of breakage to the subsurface pressures under each operation yields a prediction of percentage of artefact-type breakage. From this correlation, relationships are observed between vehicle specification, subsurface pressure generation, and consequential artefact breakage.

The achievements provide knowledge about how field operations affect specific types of buried archaeology, providing a valuable asset to farmers, land managers, and regulatory bodies. It is evident that agricultural practices, choice of track or tyre type, and inflation pressures must be carefully managed if the intention is to protect or mitigate damage to buried archaeological artefacts. Thus, a contribution has been made to the development of 'best management practices' and to the specification and use of field operations relative to intended mitigation of buried artefact damage.

Dedication

~ I would like to specially thank the following most important people ~

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For the unconditional love and support that they have given me,
and for always believing in me.

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List of Notations and Symbols

m	meter
cm	centimeter
mm	millimeter
t	tonne
V	volts
mV	millivolts
h	hour
kN	kilonewtons (force)
g/cm^3	grams per centimeters cubed (density)
kph	kilometers per hour (velocity)
psi	pounds per square inch (pressure)
kPa	kilopascals (pressure)
bar	pressure: 1 bar = 100 kPa = 14.5 psi
ANOVA	Analysis of Variance
LSD	least significant difference
SE	standard error
d.f.	degrees of freedom
P90	90th percentile
σ_n	normal stress distribution
p_m	average ground pressure
ln	natural log base e
P	proportion (as percentage)
n	number of objects in each trial
r	number of survivals (number of objects that did not break) in each trial
β	slope
α	intercept
χ	peak subsurface pressure
exp	exponential mathematical operation
2wd	two wheel drive vehicle
4wd	four wheel drive vehicle
ASCII	American Standard Code for Information Interchange

GPS	global positioning system
RTK	real time kinematic
CT	controlled trafficking
non-CT	non-controlled trafficking
LGP	low ground pressure
MGS	modern ground surface
SFT	sharp force trauma
BFT	blunt force trauma
UK	United Kingdom
USA	United States of America

Chapter 1: Introduction

1.1 Background

An important historical resource in England is buried archaeology. This resource, when located within any actively managed land area, can be damaged by surface loading from field operations, animals, or other agents. This damage to buried archaeology is unsettling, as the destruction this heritage eliminates opportunities for future development of knowledge and education. Buried archaeology is present throughout much of England and is under significant threat. Nearly 3000 scheduled monuments lie under intensive cultivation or livestock farming (English Heritage, 2003) and in the East Midlands (UK), one third of all scheduled archaeological monuments are classified as vulnerable to damage from agricultural operations. Even where farmers, land managers, and archaeologists know that archaeology exists, they might not be aware of how field operations could damage subsurface artefacts.

Given the importance of buried archaeology to national heritage and the priority of artefact protection an appropriate level of regulation is required; the development of which should be informed by evidence about how buried artefacts may or may not be damaged. Prior to this study, no work has been done to identify thresholds for artefact damage. Archaeologists excavating within agricultural contexts report that undamaged finds (for multiple artefact types) usually appear around 1 m below modern ground surface (MGS). Within the soil profile, from 250 mm to 1 m depth, there is a zone where objects might be indirectly affected by soil deformation, pressure transfer, or long-term irreversible soil compaction. Within the top 250 mm of soil, any buried objects are under threat of direct damage by tillage or other soil interventions. Unfortunately, these observations alone do not yield sufficient information to enable farmers, land managers, or archaeologists to manage or monitor field operations in a way that minimizes damage to buried artefacts. Without a full understanding of how artefacts within cultivated soils are damaged, appropriate protective regulations cannot be formulated.

Although a sound scientific basis for regulatory development has been missing, protective measures have been introduced. In the United States for example, there is stringent protection of sites over 100 years old, as well as requirements for archaeological surveys on land that is planned for development, but there is a lack of active protection for buried artefacts within agricultural areas. If archaeology is found within agricultural areas in Egypt, the right to work the land is taken away, and it remains unproductive unless or until the archaeology can be excavated and moved.

In England, the Countryside Stewardship Plan (2010) (now the Environmental Stewardship Plan, 2010) provides a subsidised opt-in control system for farmland management, but even when activated, the protection is not always easy to enforce due to a lack of monitoring systems and adequate knowledge of how field operations affect buried artefacts. As areas of England under intense cultivation are valuable agriculturally, any buried archaeology usually remains in the soil, still subjected to damaging field operations. There is a need for mitigation or other forms of buried artefact protection that can support continued production while protecting buried heritage.

Serious research aimed at exploring how buried artefacts in agricultural situations are affected and damaged by field operations began in England during the late 1970s, with a seminar organized by the Department of the Environment in 1977 on plough damage and archaeology. The resulting publication (Hinchliffe and Schadla-Hall, *e.d.*, 1980) invited continued dialogue concerning the preservation of buried archaeology in rural areas. This research however, focused mainly on the losses of artefacts due to direct contact with soil implements. Investigation into the indirect causes of damage to buried artefacts did not proceed, as there was no established method for studying this type of buried artefact damage.

More recent work has looked at the interactions between land management and archaeology. Some projects have looked at soil translocation and its role in scattering artefacts and the destruction of earthworks. These studies of soil and artefact movements also investigated the effects of field operations on soil stratigraphy and archaeological interpretation. A study was conducted by Hyde *et al.* (2010) investigating the effect of new construction work on underlying artefact deposits. This developed a stochastic model for damage to archaeological artefacts due to new construction work. There does not, however, appear to be any significant research into how artefacts within agricultural contexts might be damaged indirectly by agricultural or other operations. Nor are there management plans created for use within an agricultural context to monitor or regulate activities and protect buried archaeology.

Research into the soil dynamics and breakage processes surrounding field operations and buried objects is vital in order to inform guidance plans that might function acceptably for farmers, land managers, and archaeologists alike.

1.2 Aim

The aim of this work is to investigate the influence of surface loading from conventional field operations on buried artefact damage that will provide a sound basis for successful strategies for the future management of buried artefacts located in agricultural soils.

1.3 Objectives

The specific objectives of this research are:

- To investigate the influence of surface loading and resulting breakage relating to the material strengths of buried objects - terracotta, ceramic (unglazed), and aged bone.

- To assess the magnitudes of peak subsurface pressures transferred through soil under the dynamic surface loading from tyres and other field operations.

- To develop and test a model for predicting the effects of subsurface pressure application on buried objects from surface loads

- To explore ways of identifying the potential for damage to buried artefacts under agricultural and other field operations

1.4 Looking ahead

Achievement of this aim and these objectives will provide knowledge about how field operations affect specific types of buried archaeology. The predictive modelling of subsurface artefact breakage will support predictions of artefact breakage within the upper layer of the soil profile, providing a valuable asset to farmers, land managers, and regulatory bodies. This knowledge will support an informed understanding of buried object damage and how further loss of national heritage can be mitigated or prevented.

Chapter 2: Literature Review

2.1 Buried artefacts damage by pressure transfer in cultivated soils

There is variety in how archaeology is practiced and expressed within the literature.

In the USA, archaeology is a subfield of anthropology (Nawrocki, 1996a). Specifically, "Archaeology is the systematic study of human societies from the past using the items they left." (Nawrocki, 1996b, p. 1) For example, archaeological theory in the USA tends to place more importance on construction of a scientific and comparative archaeology, and promotes the use of the scientific method. Archaeologists emphasize a scientific approach to inform the archaeological context and analysis of cultural processes within a specified framework.

In the UK, archaeological theory is sometimes viewed as a subfield of history rather than anthropology (Nawrocki, 2009) and is presented as a transdisciplinary field. For example, at the University of Oxford, the study of archaeology is within the Faculty of Classics, where one of its two sub-faculties is Ancient History & Classical Archaeology (http://www.classics.ox.ac.uk/). Oxford does however, have an undergraduate course for 'archaeology and anthropology,' and information on its website explains that "Today both subjects involve a range of sophisticated approaches shared with the arts, social sciences and physical sciences" (http://www.ox.ac.uk/admissions/undergraduate_courses/courses/archaeology_and_anthropology/archandanth_4.html). Thus, it seems to be defined in a way that retains some level of non-experimental evaluation, allowing site interpretation to acknowledge subjective evaluation, while recognizing and working within a mental framework that retains relativity, and recognizes the distance in perspective created by the passage of history.

Assessment of the literature indicates that sometimes in practice archaeology is not always treated as a science. Case studies abound, and observational and anecdotal conclusions often form a basis for trends in archaeological theory about buried artefacts within cultivated soils. Nonetheless, archaeology is an established discipline that reflects advances in theory, science, and new discoveries. Certainly, it is not as process-based or mathematically-founded as agricultural engineering theory relating to soil stresses and strains.

Interestingly, in the USA, a subfield of anthropology exists that responds in a much more scientific manner to some of the same questions driving archaeologists. Forensic anthropology is "the application of anthropological research and techniques to the resolution of medicolegal issues" (Nawrocki, 1996a, p. 1). Within forensic anthropology, two further subfields exist (Nawrocki, 2009). Forensic archaeology is "the application of archeological methods to the resolution of medicolegal issues" (Nawrocki, 1996b, p. 1). Forensic taphonomy relates to human remains, and "examines how taphonomic forces have altered evidence that is the subject of a medicolegal investigation" (Nawrocki, 1996c, p. 1). As a side note, forensic osteology is a third subfield of forensic anthropology that is frequently practiced by pathologists rather than anthropologists within the UK (Nawrocki, 2009).

Since legal cases generally require extensive and very scientific justification and documentation of procedures, and general interpretation of crime scenes, forensic scientists must inherently maintain their work accordingly (Nawrocki, 1996b). Archaeological case studies and surveys do provide observations and static records about what *happened to* buried artefacts; however they are not experimental studies. This research is interested in *how* subsurface damage may have occurred during the previous burial period. An understanding of the processes surrounding buried artefact damage will allow farmers, land managers, archaeologists, and other professions to make informed decisions to support the protection of buried artefacts by appropriate land management.

As mentioned in Chapter 1, research on buried artefact damage relative to direct damage by ploughing or other soil operations was presented as a collection of papers in the publication edited by Hinchliffe and Schadla-Hall, titled *The Past Under the Plough* (1980). The seminar from which the publication came was organized by the Department of the Environment and the Wessex Archaeological Committee at Salisbury (February 15, 1977). In the forward of the publication, Saunders noted that:

> "There is an urgent need to examine the effects of ploughing on a more factual basis; to understand the various methods of cultivation and the ways these might affect archaeological material in different conditions; to establish how far and in what circumstances ploughing is destructive and whether it is possible to recover useful archaeological evidence even from sites where the soil has been repeatedly turned over." (1980, p. 8)

A part of the seminar focused on the effects of cultivation techniques on buried archaeology. One paper (Hinchliffe, 1980, Pp. 11-17) provided an overview on the specific 'Effects of ploughing on archaeological sites: assessment of the problem and some suggested approaches'. A second paper (Lambrick, 1980, Pp. 18-21) explored the 'Effects of modern cultivation equipment on archaeological sites'. Another paper (Bonney, 1980, Pp. 41-48) was titled 'Damage by medieval and later cultivation in Wessex'. Also included was 'The Sussex plough damage survey' (Drewett, 1980, Pp. 69-73), 'Ploughing on archaeological sites in Norfolk: some observations' (Lawson, 1980, Pp. 74-77), and 'Measurement of plough damage and the effects of ploughing on archaeological material' (Reynolds and Schadla-Hall, 1980, Pp. 114-119).

Some of the other papers provided background material for the participating archaeologists on agricultural techniques, while others focused on case studies of archaeological sites or more general comments on regional archaeology relative to the site environment type (forest, field).

Within the first paper, Hinchliffe (1980) acknowledges the concerns within the archaeological community over damage to artefacts within cultivated sites. He notes that "...today's most heavily cultivated areas are those which in the past have tended to attract settlement and have hence acquired a greater density of archaeological sites" (p. 11). Hinchliffe then continues to explain the complexity of the issue. He argues that while damage to buried archaeology by agricultural cultivation is recognized and appreciated as a major issue, the extent of the damage depends on a "complicated interaction of variables" (Lambrick, 1977; in Hinchliffe, 1980, p. 11). These variables and their significance, he states, remain undefined. He states:

> "A statistical examination of many of these aspects would be a valid and useful approach to the problem. Meaningful data on which such a statistical approach might be based are almost entirely lacking." (p. 11)

The remainder of the paper covers aspects of ploughing, and includes observations of artefact damage. He also comments on the general approach taken towards plough damage and proposes some experiments that would help quantify plough damage.

Hinchliffe's final summary of recommendations calls for the "formulation of an overall policy ... on the ploughing problem" (p. 17). He realizes that data are needed before policy can be formulated, and suggests various experimental programmes and site monitoring techniques to achieve this. He seems interested in a multi-disciplinary solution, as he encourages archaeologists, agriculturalists, and other groups to come together over "developments in the agricultural landscape" (p. 17). Therefore, there is focus on the particulars of direct damage to buried archaeology from ploughing, but not much mention of the potentially damaging indirect effects of surface loading.

Lambrick (1980) briefly covers the variables surrounding the effects that ploughing and associated activities have on buried artefacts. He states "...a consideration of some of the effects which can be reasonably expected" (p. 18) within any individual archaeological site under cultivation, and presents a ranking of the severity of threat to archaeology from cultivation as follows:

> Severely threatening – "The cultivation of previously unploughed sites"
> More threatening – "The deeper cultivation of sites on existing arable"
> Less threatening – "The effective deepening of cultivation as a result of erosion"
> Least threatening – "Damage to artefacts within the plough-soil"
> (Pp. 18-19)

Lambrick also discusses variations to the threat from ploughing relative to other agricultural implements and operations. He notes at one point "...most machines are likely to penetrate deeper where soft features occur" (p. 19), recognizing that there could be some *indirect* damage to buried archaeology, but without further clarification it must be assumed that he is referring to direct damage by a plough or other agricultural implement.

Lambrick concludes "The aim has rather been to point out the ways in which some technical knowledge can help ... assessments [of site condition or threat of damage]" (p. 21); he is interested in finding ways to better analyse the overall situation and provide informed recommendations to help protect archaeological sites under cultivation.

Bonney (1980) explained how damage to archaeological sites is not limited to the recent history of modern cultivation techniques, being concerned mostly with post-Roman cultivation, and uses Wessex as a case-study area.

Drewett (1980) presented a survey that established "the condition of all known archaeological sites in rural Sussex" (p. 69) "to advise on what action should be taken at each site" (p. 69). Lawson (1980) presented observations (not a survey) from archaeological sites in Norfolk on plough damage. Both these papers were focused on direct damage from ploughing and did not discuss indirect damage caused by other agricultural operations.

Reynolds and Schadla-Hall (1980) highlight the "urgent need to be able to assess and quantify agricultural damage in order to establish guidelines for excavation and conservation" (p. 114) and propose experimental work to assess plough damage to artefact shards and buried structures. They note that the experiments would allow "rapid appraisal of the effects of plough damage, subsoil degradation, soil movement and feature destruction as well as the study of the effects of ploughing on features and artefacts below the ploughsoil" (p. 122).

The published proceedings of the 1977 seminar proved important in raising the public profile of damage to buried archaeology by agriculture; however, the focus remained on obvious direct damage from ploughing, and not damage caused by surface loading during other agricultural operations.

In 1998 a comprehensive 'Monument's at Risk Survey' was performed by English Heritage (Darvill and Fulton, 1998). This study identified agriculture as an active agent of destruction for buried archaeology, in the past as well as the present. The study estimated that 10% of all cases of destruction and 30% of the cumulative damage over the past 50 years to archaeology in England were due to agricultural activities. It also estimated that 65% of the surviving 'monuments' remained at medium or high risk of damage from current agricultural activity.

A smaller regional follow-up survey was conducted by English Heritage as the 'East Midlands Scheduled Monuments at Risk' study (English Heritage, 2006). This survey found that cultivation was the major cause of damage to 10% of 1493 scheduled monuments within the study, with 88% of those monuments remaining at a high risk of further damage from cultivation.

Around the same time, a book titled *Advances in Forensic taphonomy: Method, theory, and archaeological perspectives* was published in the USA. This book was primarily associated with unrelated issues within the field of forensic taphonomy, but Chapter 7 (Haglund, Connor, and Scott, 2002, pp. 133-150) directly addressed 'The effect of cultivation on buried human remains,' and outlined the approach taken on the issues involved with plough zone archaeology as follows:

> "Plow zone studies follow three general lines of inquiry.
> 1. Interpretation of surface collections and their relationships to their original locations
> 2. Displacement of artefacts both horizontally (lateral) and vertically
> 3. Damage to the material from cultivation activities"
>
> (p. 139)

The authors identify bone damage by "mechanical abrasion and breakage" (p. 140), occurring "as heavy machinery rolls over subsurface, or surface, elements ... not only during plowing or primary field tillage, but any time that machinery is run over the field" (pp. 140-141). This inference warns that damage to buried artefacts can and does occur in an indirect manner during field operations.

In 2003, English Heritage began a campaign for further protection of buried artefacts within cultivated sites (English Heritage, 2003). In 2004, the UK government agreed to review 'Class Consent (English Heritage, 2009) for agriculture, which is an agreement that allowed ploughing to the maximum depth reached in the preceding six years without exceeding 0.3 m, prohibiting other landwork operations. This prompted funding for various experimental studies.

A primary study resulting from this was the Conservation of Scheduled Monuments in Cultivation (COSMIC) project (Oxford Archaeology, 2006). This study provided empirical data indicating that a specified restricted cultivation depth would be preferred to Class Consent.

Subsequent and further research from the COSMIC project was recommended (by the UK government) into aspects of the risk of damage to buried archaeology from cultivation. This led to the project within which this research was conducted and included a systematic exploration of mechanisms of indirect damage from pressure transfer under surface loads.

As no archaeological literature was found stating the relationship between damage to buried artefacts (of any origin and type) and subsurface pressures from field operations, other areas of study were explored. While there did not seem to be any studies relating to damage to ceramic artefacts and field operations, the field of taphonomy (as mentioned previously) does focus on human remains. Kiley (2008) conducted research on cultivation-related damage to surface-deposited bone artefacts. She examined "the distribution, damage, and loss of bone caused by two years of agricultural practices at a farm in northwest Indiana." The study was performed within a forensic context, relative to current cases within forensic investigations (on non-aged pig skeletonised and mummified carcasses). Although it was not performed as an archaeological study, archaeological methods were utilized throughout the study.

The flat plain of well-drained sandy loam found in the glacial-till of northern Indiana (Nawrocki, 2009) is used predominantly for pasture and agriculture, with farmers mostly cropping corn, soybeans, and wheat (United States Department of Agriculture National Agricultural Statistics Service, 2003). Evidently by default, this agricultural landscape becomes a common location for crime scenes and related human remains. According to Kiley (2008), the agricultural practices "hinder the processing and interpretation of a forensic scene by altering its context and dispersing its human remains" (p. 1). She describes the "taphonomic profile" (p. 3) that surface-deposited bones would adhere to, and describes the types of damage in terms of either sharp force trauma (SFT) or blunt force trauma (BFT) that is usually observed.

SFT is considered any damage caused by a sharp object: "Sharp force trauma (SFT) is damage that is created by bladed or sharp objects. These modifications tend to exhibit clean margins, are V-shaped in cross section, and follow a distinct plane." (Kiley, 2008, p. 28).

BFT is a much broader classification of bone damage. Nawrocki (2009) helped clarify the damage type, providing the following explanation:

> "BFT encompasses the entire range of pressure-caused fractures, including on the one hand actual focal (narrow) contact with specific objects (like a hammer or a plow blade) or simply by accumulated pressure of soil and stones (applied very broadly) on a bone buried below the surface. BFT is therefore somewhat non-specific, in contrast to other types of bone injury, such as gunshot wounds (GSW) or sharp force trauma (SFT) caused by a knife."

BFT is thus the type of damage classification that would apply to buried bones damaged indirectly by pressure transfer underneath any applied surface loading.

Although Kiley's research focused on surface deposits of non-aged bone, this study provides some insights about the survival of surface artefacts in an agricultural setting. The conclusions from Kiley's thesis that are most relevant to the research presented here relate to the observed size gradient of bones recovered from cultivated soil, as well as the types of trauma that the bones sustained relative to mouldboard and disc ploughing (both types of ploughing were performed within the field plots).

Kiley found that "Larger bones were recovered more frequently than small bones." This 'sorting' of bone sizes during cultivation was confirmed within Kiley's literature review – as agricultural tillage machinery creates gaps and crevasses within the soil medium that allows smaller items to fall and sink down into the soil profile, while larger items remain on the soil surface. Kiley states "Farming machines are designed to bring clods and other inclusions to the surface for removal, and so larger artifacts may come to the surface while smaller artifacts remain buried" (p. 16).

The trauma sustained by the bones during the study could have come from any of the agricultural operations performed in the experimental areas of the two fields. Kiley (2008) investigated damage observed on complete as well as fragmented bones, and observed both SFT and BFT. From the field subjected to disc ploughing, "39% of bones recovered have at least one incident of sharp force trauma and 51% have at least one incident of blunt force trauma" (p. 59). From the field subjected to mouldboard ploughing, "65% of recovered bones have at least one incident of sharp force trauma and 86% have at least one incident of blunt force trauma" (p. 59).

From the bones suffering BFT, Kiley categorized the BFT fractures by type. The BFT bone damages were tallied under the categories of complete fracture, transverse, oblique, spiral, butterfly, crushing, or puncture. It should be noted that the BFT categories the author would expect in a situation where the artefact was buried entirely under the plough layer would probably include the transverse, crushing, and puncture fracture types. In Kiley's research, the percentage of bones broken by BFT (any type) from cultivation was 50.6% in the disc ploughed field, and 85.6% in the mouldboard ploughed field. Within the disc ploughed field, the transverse fractures accounted for 10.1%, the crushing type accounted for 6.5%, and the puncture type accounted for 0.8% of total bone fracture. Within the mouldboard ploughed field, the transverse fractures accounted for 24%, the crushing type accounted for 4.8%, and the puncture type accounted for 3.2% of the total bone fracture.

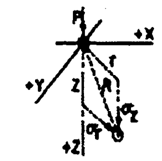
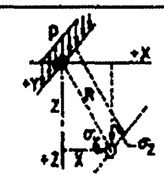
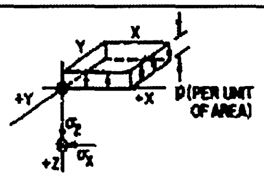
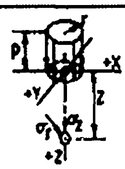
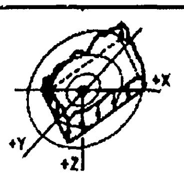
Of course there are multiple factors affecting these rates of BFT relative to the total number of bones, especially because much of the damage was most likely caused by direct contact with a tillage implement in the field. In addition, Kiley notes that "One difficulty with simple tallies of traumata is that longer bones are expected to display a higher incidence of trauma merely because they have more surface area." (p. 54). The results from her research are very interesting however, as they indicate general relationships that are forming between cultivation type, bone size (which is relative to bone type), and damage type.

Although Kiley's research was performed using non-aged pig surface-deposited bone (neither human nor aged bone; not any other type of artefact material, not buried) the subject of the study has many parallels with the study of damage to buried artefacts within cultivated fields in England. The situational context is the same, and although Kiley's work was performed in a forensic context, the focus on the process of damage to bones in the field was evident.

It is evident that there is a gap in the literature relating to indirect damage to buried artefacts caused by soil surface loading.

2.2 Pressure transfer through soil

Theory on subsurface pressure transmission under surface loading falls within the area of continuum soil mechanics (Vyalov, 1986) and is concerned with the measurement and prediction of in-soil stresses and stress-states. Boussinesq (1885) defined the outlining principles of pressure prediction in a homogeneous, isotropic, weightless, linear elastic semi-infinite medium under surface loadings; since his time, other researchers have utilized, modified, improved, and expanded his research (Frölich, 1934; Söhne; 1958; Chen and Baladi, 1985; McCann, 2002; Trautner, 2003). Figure 2.1 shows the formulas used for calculating subsurface stresses from surface loading used by the Naval Facilities Engineering Command (1986) for semi-infinite, elastic, isotropic, and homogeneous foundations.

LOADING CONDITION	STRESS DIAGRAM	STRESS COMPONENT	EQUATION
POINT LOAD		VERTICAL	$\sigma_z = -\frac{P}{2\pi R^2}\left[\frac{-3r^2 Z}{R^3} + \frac{(1-2\mu)R}{R+Z}\right]$
		HORIZONTAL	$\sigma_r = \frac{P}{2\pi}\left[3\frac{r^2 Z}{R^5} - (1-2\mu)\left(\frac{R-Z}{Rr^2}\right)\right]$
		SHEAR	$\tau_{rz} = \frac{3P}{2\pi} \cdot \frac{rZ^2}{R^5}$
UNIFORM LINE LOAD OF INFINITE LENGTH		VERTICAL	$\sigma_z = \frac{2p}{\pi} \cdot \frac{Z^3}{R^4}$
		HORIZONTAL	$\sigma_x = \frac{2p}{\pi} \cdot \frac{x^2 Z}{R^4}$
		SHEAR	$\tau_{xz} = \frac{2p}{\pi} \cdot \frac{xZ^2}{R^4}$
UNIFORMLY LOADED RECTANGULAR AREA (FIGURE 4)		VERTICAL (BENEATH CORNER OF RECTANGLE)	$\sigma_z = \frac{p}{4\pi}\left[\frac{2XYZ(X^2+Y^2+Z^2)^{1/2}}{Z^2(X^2+Y^2+Z^2)+X^2Y^2} \cdot \frac{X^2+Y^2+2Z^2}{X^2+Y^2+Z^2} + \tan^{-1}\frac{2XYZ(X^2+Y^2+Z^2)^{1/2}}{Z^2(X^2+Y^2+Z^2)-X^2Y^2}\right]$
UNIFORMLY LOADED CIRCULAR AREA (FIGURE 5)		VERTICAL	$\sigma_z = p\left\{1 - \frac{1}{[1+(r/Z)^2]^{3/2}}\right\}$
		HORIZONTAL	$\sigma_r = \frac{p}{2}\left[1+2\mu-2(1+\mu)\left(\frac{Z}{\sqrt{r^2+Z^2}}\right)+\left(\frac{Z}{\sqrt{r^2+Z^2}}\right)^3\right]$
		SHEAR	$\tau_{rz} = 0$ (STRESS COMPONENTS $\sigma_z, \sigma_r, \tau_{rz}$ BENEATH CENTER OF CIRCLE)
IRREGULAR LOAD		VERTICAL	COMPUTED FROM INFLUENCE CHART OF FIGURE 10

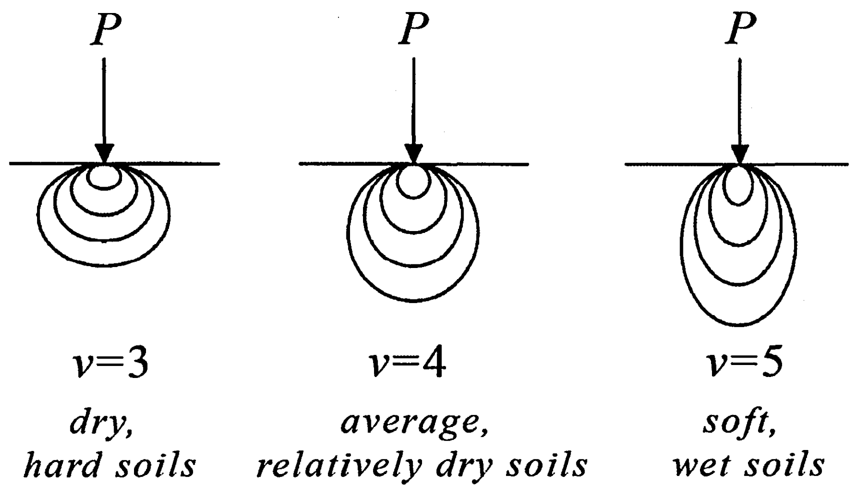
ASSUMED CONDITIONS · APPLIED LOADS ARE PERFECTLY FLEXIBLE. FOUNDATION IS SEMI-INFINITE ELASTIC ISOTROPIC SOLID.

After Naval Facilities Engineering Command, 1986; in Dain-Owens, 2006.

Figure 2.1: "Formulas for stresses in semi-infinite elastic foundation"

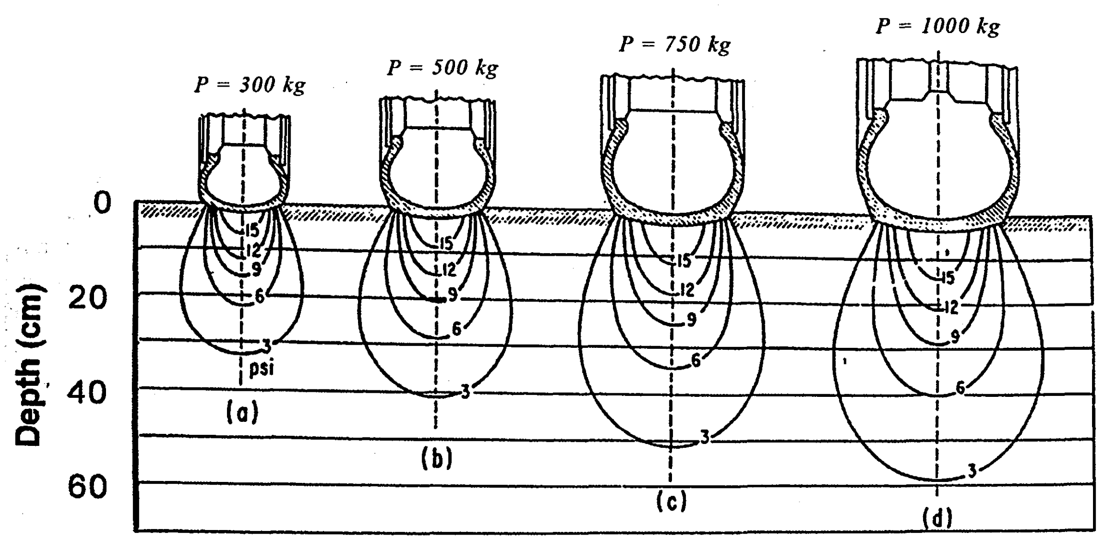
Presentation of Boussinesq equations for calculating stresses attributed to specific loading conditions in soil.

Of the various researchers after Boussinesq, Söhne (1958) played a major role in the development of in-soil stress prediction theory. Boussinesq had studied the prediction of stress levels and stress distribution under surface loading. Söhne investigated the effects of contact pressure and applied load magnitude. He found that the soil properties (hard-dry versus soft-wet) had a significant effect on the magnitude and depth of pressure transfer (see Figure 2.2), and that the amount of load affected the maximum depth of stress penetration (see Figure 2.3).



After Söhne, 1958; Dain-Owens, 2006. Not to scale.

Figure 2.2: Diagram of stress concentrations around the axis of applied load for different soil types.



After Söhne, 1958; in Håkansson, 2005 and Dain-Owens, 2006

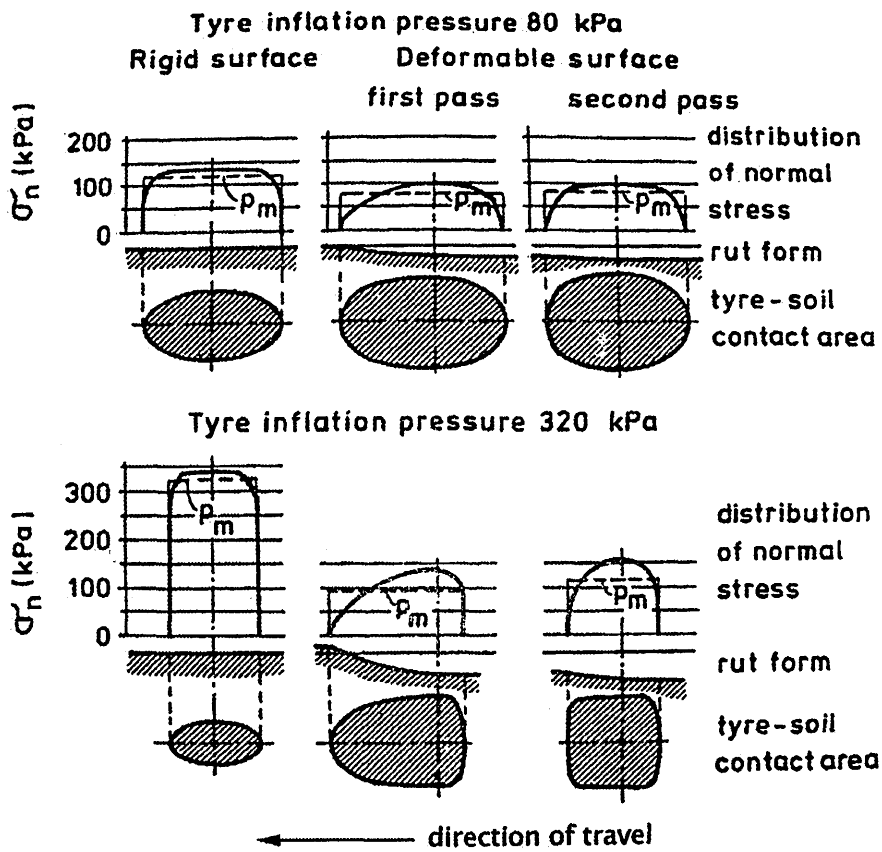
Figure 2.3: Predicted major principal stress at different depths in the soil under wheels loaded by increasing loads.

Matching relative dimensions maintained surface pressure of 0.83 bar for every case. The stresses are shown in vertical sections through the soil, perpendicular to the direction of travel and through the centre of the contact area.

Figures 2.2 and 2.3 provide an accessible visual presentation of an important concept relative to an understanding of pressure propagation in soil. In both figures, a surface load is applied to the soil, and graduated bulbs of pressure are shown in the soil profile below. In both figures, the pressure bulbs extend deeper into the soil as either the soil becomes weaker or the load increases. In Figure 2.3 the pressure magnitude at each grade is labelled, showing that the highest pressure propagation is retained in the more shallow layers of the soil. Håkansson and

Söhne demonstrate that there is a reduction in subsurface pressure as the soil profile depth increases. This concept is well established in the study of soil dynamics, and this property of pressure propagation in soil can usually be assumed although soil properties and other factors control the exact manifestation of pressure attenuation (Wulfsohn, 2009b).

Söhne also investigated pressure propagation relative to the properties of both the soil and load type. One specific interest was the effect of different magnitudes of tyre inflation pressure (see Figure 2.4).



After Söhne, 1953; in Wulfsohn, 2009

Figure 2.4: Two tyre inflation pressures and 'footprints' on both a rigid and a deformable surface.

"Contact areas, normal stress distributions σ_n, average ground pressure p_m, and rut longitudinal shape of a moving 17-20 implement tire with a load of 3.8 kN for two inflation pressures, two wheel passes, and on rigid and deformable surfaces" (Wulfsohn, 2009, p. 61). This figure is included in order to help demonstrate the effect of tyre inflation and surface deformation on contact area and in-soil pressure propagation.

Figure 2.4 shows two tyre inflation pressures and their footprint on both a rigid and deformable surface. This footprint is called the 'contact area' of the tyre, and "refers to the portion of the wheel or tire in contact with the supporting surface" (Wulfsohn, 2009a, p. 59). The contact area of the tyre or track under any field operation is what supports the load of the vehicle. In general, if the contact area is smaller for a given load, the ground pressure increases. If the contact area increases for the same load, the ground pressure decreases. Both tyre inflation and the ability of the surface to deform determine the size of the contact area. A tyre with higher inflation pressure cannot deform as much as one with lower inflation pressure, and thus the contact area between the tyre and the soil will become smaller. A tyre with a low inflation pressure becomes quite flexible, and by deforming, more of the tyre comes into contact with the soil surface and the contact area becomes larger. This basic relationship extends into the pressure propagation under the surface load as well. If the contact area is smaller and thus the contact pressure is higher, the loading of that area of soil increases and the pressure will be transferred down through the soil profile. If the contact area is larger, the contact pressure decreases, the loading of the soil area also decreases and less pressure is transferred through the soil profile.

Figure 2.4 also demonstrates the difference between static and dynamic loading. In static loading, there is only a perpendicular, or vertical force applied to the soil surface. A dynamic load occurs when the tyre or track moves along a linear path over the soil.

The above factors all affect in-soil pressures (no matter what type of agricultural load has caused them), and must all be taken into consideration in the development of any model that aims to predict in-soil pressures.

Recent developments of the soil pressure theory have been applied within the context of soil state and soil compaction prediction. O'Sullivan et al. (1998) developed the COMPSOL model, which used numerical modelling for compaction by wheels by Smith (1985). Keller et al. (2007) adapted various soil models into a more useable, improved format to create the SOILFLEX model. Both models are based on critical state soil mechanics, and thus need various input data.

In general, critical state soil mechanics utilizes parameters that make up a system of state variables. Input data includes but is not limited to a selection of soil temperature, deformation (strain), and stress measurements (Fredlund and Rahardjo, 1993). Söhne also used a concentration factor (see Figure 1.2; added to the Boussinesq equations in 1934 by Frölich) that has since been proved to relate to the soil type, soil moisture content (Söhne, 1958), precompression stress (Horn, 1991), soil structure, contact area, and contact stress (Horn and Lebert, 1994).

The COMPSOL and SOILFLEX models both use the concentration factor introduced by Frölich and connected to soil parameters by Söhne and the other researchers. The soil models also make use of a particular soil's virgin compression line, and if this (hard to obtain) data is available, the models seem to work relatively well for soil stress prediction.

Håkansson (2005), in his review of soil compaction, contended that the existing analytical models used for predicting magnitudes of soil stresses under surface loads were producing satisfactory results. These models however, should not be used for the prediction of pressure application *onto* buried objects. This is because the detected pressures may differ in this situation compared to in-soil stresses used within critical state soil mechanics (Wulfsohn, 2009b). This is because the pressure application on any buried object depends not only on the properties of the soil, but also the mechanical properties of the object and the differences primarily in stiffness between the soil medium and object material.

This topic is discussed by Wulfsohn (2009b) in relation to the use and choice of stress transducers to experimentally sense soil stresses under various types of loading. "If the transducer is stiffer than the soil then stresses concentrate on the transducer, whereas if the soil is stiffer than the transducer, arching will occur around the transducer so that the surrounding soil carries toad." (p. 90). She also notes that if the soil is disturbed around the pressure transducer during installation, the response of the soil and thus the magnitude of the soil stress may be affected.

The above issues are obstacles that agricultural engineers, interested in experimentally recording very accurate soil stresses within the soil medium, must overcome. However, in relation to buried artefacts, these issues do not seem to affect buried artefact damage.

Buried archaeology within the soil profile can be of any material, shape, or size. The differences between soil and buried artefact stiffness can be considered a type of pre-existing condition. Each artefact, depending on its type, shape, and material will have its own relationship with the surrounding soil, and each will react accordingly. Therefore, a researcher intent on recording applied pressure on a buried artefact should be most concerned with how well the properties of the pressure transducer and the buried artefact match.

Also, depending on its age, a buried artefact will have existed within a particular soil profile for some time. Its original deposition into the historical record could have happened by way of a range of processes. The artefact may have been thrown away or been treated similarly with other forms of detritus. The artefact may have been more carefully buried alongside the deceased as a grave offering within a burial site. Small insects, rodents, or other biological agent may have disturbed the surrounding soil at the time of or sometime after burial. Preferential water flows during extremely wet periods could have changed the soil matrix, or some form of human activity could have modified the soil in which the artefact was buried.

However the artefact ended up in the soil profile, some disturbance to the surrounding soil matrix would most likely have occurred either at the time of burial or at some point during its rest within the soil. Because of the large opportunity for soil modification around the artefact, any research utilizing pressure transducers to investigate the pressure application onto a buried artefact should recognize that a small amount of soil disturbance should not threaten the integrity of the research since the situation in fact better represents a 'real' buried-artefact scenario.Whether the subsurface pressures are measured in a way that best reports soil stresses or pressures on buried objects, surface loading will generate subsurface pressures. Therefore, it is important to have some idea of what the magnitudes these pressures might be.

Within the scope of this research, agricultural operations define the most relevant load type. The exact types of vehicles and the exact subsurface pressures differ from between farms, regions, and countries, but there are general types of machinery and tillage implements. Tractors, big or small, wheeled or tracked, make up a large portion of the vehicles passing over arable land. A variety of implements and other agricultural tools are generally pulled behind these vehicles to perform multiple tasks in the field. There is an array of vehicles available to farmers for spraying and fertilizing crops. Heavier vehicles, such as harvesters and tractor-trailer operations are also used on cultivated fields. Light off-road quad-vehicles are also used by farmers for certain tasks.

All these vehicles have been studied in many ways by the agricultural engineering community. New developments, ideas, and concepts are constantly being created to advance agricultural technology. But the surface loading of the soil remains a constant consequence of agriculture.

Much research has been done on soil stresses under agricultural machinery. Various studies compare soil stresses, each of them under a limited range of vehicles with or single tracks and/or tyres (inflated and loaded to specification) (Arvidsson and Keller, 2007; Bailey et al, 1996; Blackwell and Soane, 1978; Blackwell and Soane, 1981; Christov, 1969; Horn, Way, and Rostek, 2003; Pytka and Konstankiewicz, 2002; Lamandé, Schjønning, and Peterson, 2006; Lamandé et al, 2006; Mogilevets and Khallyyev, 1977; Pytka, 2001; Raper and Arriaga, 2005; Pytka, 2005; Schjønning et al, 2006; Way et al, 1997). There are also studies that measure subsurface soil stresses using one or two vehicles, tyres, and/or tracks, specified accordingly, to investigate certain aspects of soil mechanics and inform soil models, especially relative to soil compaction (Abu-Hamdeh and Reeder, 2003; Ansorge, 2007; Bakker, Harris, and Wong, 1995; Gysi, Maeder, and Weisskopf, 2001; Way et al, 1996; Wiermann et al, 1999).

The existing literature, while it does contain many small 'case-studies' with information on magnitudes of subsurface pressures under various selected agricultural operations, does not provide any single reference that catalogues the subsurface pressures generated under an entire year of agricultural operations at specific depths within a specific soil type. While the various small studies could be sought out, and the relevant subsurface pressure information extracted into a comparative format, this would still not present an accurate or complete account of the situation. This is largely due to variation within and between researchers' methods and experimental limitations. This is also due to the many different soil types and soil environments that are used for experimental work.

This is important to note, as it highlights that the existing research is composed mostly of sets of narrow studies where a small range of tyres or agricultural load cases are investigated within specified soil types for surface or subsurface pressure generation. With so many sources of variability in the pressure sensing of field soil, as well as in the many existing iterations of farm machinery and field operations used between research studies, it remains impossible for the identification of specific conclusions relating to the entire set of agricultural operations used by one farmer over the course of a full year within a particular soil type of his field.

As it stands, there is no full record of the magnitudes of subsurface pressures that might offer all the information relative to any one particular buried-artefact case. This information would be very useful, if not necessary, for anyone interested in knowing how buried artefacts might react in a cultivated field.

2.3 Soil parameters as indices of soil resilience and sustainability

In addition to addressing the factors that would have an immediate mitigating effect on the manifestation of indirect damage to buried artefacts, it is important to recognize that the quality of short and long-term management of a soil resource can either amplify or reduce damage to buried artefacts. Good soil management involves recognizing that any "anthropogenic intervention" (Lal, 1994, p. 43) to a soil will have either a positive, neutral, or negative effect on the longterm soil condition, and appropriately choosing field operations to encourage the maintenance of a resilient soil.

Soil resilience, as a concept, is context-based, and therefore its definition depends on the situation. Soil resilience can refer to the functionality and performance of the soil system, alternatively, to the soil's physical structural integrity. It can be viewed in relation to the soil's ability to either recover from applied stress, or resist change from an applied stress (Estwaran, 1994, pp. 24-25). Within the context of this research, soil resilience is best related to the structure of the soil and its ability to resist change from applied stress that has potential to degrade the soil structure.

Any physical manipulation of soil by agricultural operations will modify the soil's physical structure, with the effect of modifying the function, or performance, of the soil (Lal, 1994, p. 54). Agricultural operations are generally performed with the intention of improving the physical aspect of the soil so that it can provide a better medium for seeds to germinate, plants to grow, and for a crop to thrive. However sometimes irreversible damage can be caused if the soil condition is not right for the operation (e.g. too wet), or the operation is not fit-for-purpose (e.g. too heavy). Soil that is mistreated in such ways becomes degraded, weaker, and more vulnerable to further damage. The loss of structural resiliency in the upper layers of the soil profile exposes the deeper layers to higher magnitudes of pressure transfer and more opportunity for compaction and deformation. Buried objects within these deeper layers of soil such as buried artefacts become more vulnerable to damage by surface traffic. Thus, managing soil to promote resiliency potentially increases its ability to resist pressure transfer through the soil profile, mitigating or even preventing damage to buried artefacts.

The successful farmer (in relation to securing not only high crop yields but long-term field-soil health and sustainability with minimum external inputs) requires an intimate knowledge of the soil system. The soil medium will provide years of harvest provided it is healthy and resilient. If cared for properly, the soil resource can provide resistance to environmental changes, such as drought, flood, freeze, heat. Plants growing in any soil medium thrive with a healthy soil system, as their above-ground biomass depends on the below-ground biomass to properly function.

With today's modern approach to agriculture that involves the use of many large, heavy, and implement-pulling vehicles and machinery, it would be good sense to attempt to maximise the resilience of the soil medium. Protecting the surface levels of the soil as well as the subsurface depths of the soil profile from irreversible damage would be a key focus in achieving this aim. If the soil layers are protected from over-loading, deep compaction, and other physical damages, any surviving historical artefact residing within the soil medium has a better chance of surviving intact. Therefore, preventing damage to the soil profile and soil system helps to allow proper soil chemistry, nutrient cycling, and biological activity.

Agricultural engineers, like farmers, must have an adequate working knowledge of the soil system. They must be interested in the aspects of the soil system, but they will inevitably view the soil system and soil properties relative to any agricultural vehicle or implement. Farmers must, from time to time, deal with broken machinery or other field-working issue, so they too are able to take a similar viewpoint as an agricultural engineer. They will focus on the realm of effects that the soil can have on the machine, or that the machine can have on the soil, and thus the presentation of the basic soil system, soil properties, issues and opportunities relating to the soil-vehicle/machine relationships will be classified and dealt with differently than would, for example, a soil scientist, soil biologist, or even a soil engineer. Agriculturalists (a loose term used by the author to include both farmers and agricultural engineers) thus define the soil and its properties relative to its immediate function.

In the UK, soil is commonly described by iterations of its physical state – relative to type and structure, as classified by the soil series classification system (King, 1969). The seedbed created in any field irrespective of soil series is described by the word "tilth." Andrade-Sanchez and Chancellor (2009) provide a useful explanation of soil *tilth* and the theory behind its relation to the agricultural machinery. "Tilth is the result of a combination of many physical soil properties, but the most common expression of tilth in tillage studies is related to the structural state of soil." (Andrade-Sanchez and Chancellor, 2009, p. 345). It is considered to be a "tillage-induced state of soil," (Andrade-Sanchez and Chancellor, 2009, p. 345) that can be analyzed by investigating soil particle size, soil strength, and soil aggregate stability (Voorhees and Lindstrom, 1984). The quality of soil tilth is expected to have some effect on the efficiency of the field operations to perform their specified job (Watts and Dexter, 1994). A more scientific approach even utilizes tensile strength testing of soil aggregates to dictate a measure of soil friability (Dexter, 2004). Andrade-Sanchez and Chancellor (2009) provide the background of the soil tilth relationship with agricultural machinery while at the same time recognizing that the exact "nature of the relationship between energy and soil tilth has not been established," citing a difference in scales (p. 345).

Soil can also be described in relation to its ability to provide vehicle *traction* (Wulfsohn and Way, 2009, p. 215). It seems that the two most important descriptors in this relationship are "soil normal strength (ability to resist sinkage) and soil shear strength (ability to resist horizontal deformation (Bekker, 1969; Yong et al., 1984:, Wong, 1989: Upadhyaya and Wulfsohn, 1993)" (Wulfsohn and Way, 2009, p. 215). Some of the main soil property descriptors utilized to classify soil within traction performance limits are proposed to be "gradation of particle size, porosity, bulk density, water content, shear strength parameters, plate sinkage parameters (normal strength), and cone penetration resistance (cone index);" and description of more overall features of the terrain are defined relatively, including "soil texture class, structure, and moisture status" (Wulfsohn and Way, 2009, p. 215).

The scale of the soil-vehicle relationship also affects how the soil system is described and referenced in the literature. Terrain studies focus on soil *trafficability*, as a measure of "the ability of the terrain to support and provide traction for vehicle operation" (Shoop, 2009, p. 186); where the way that the soil interacts with the vehicle's contact points is the main area of focus, and the word terrain is defined as "the material that compromises the ... soil, vegetation ... [and] the geometry of the ... surface" (Shoop, 2009, p. 186). Here there is also a need to characterize the soil surface, as there is an overall interest in predicting "off-road vehicle performance, trafficability, and soil deformation (compaction and rutting) that result from vehicle passage" (Shoop, 2009, p. 186). Shoop indicates that the descriptive parameters relative to soil trafficability are "soil type, structure, grain size distribution [same as soil particle size], Atterberg limits, water content [same as moisture content], and density," (2009, p. 187) are all important in an evaluation of trafficability, and can all be evaluated relative to an overall measure of soil strength.

In the above three 'systems' defining variations and classification of the soil-versus-machine relationship (soil tilth, traction, and trafficability), the measurement and evaluation of soil particle size (relates to soil type), soil normal strength, moisture content, soil structure (soil aggregate size is related to this) is a central theme in defining the quality of the soil-machine relationship. These four soil properties must thus be central in the evaluation of a sustainable and resilient soil medium as seen by a farmer or agricultural engineer.

Of the four soil properties, soil type and soil moisture are somewhat 'uncontrollable,' as they are inherent to a field. Soil type is a very heterogeneous soil property, and depending on the geology of the land can vary below field scale; soil moisture is controlled by the seasonality / weather conditions of the field's location. Soil strength is somewhat related to soil type and moisture, but it can change relative to the extent and type of soil manipulation imposed on the field by the farmer and so should be considered a relatively controllable factor. Soil structure is also related to soil type, but it too depends on the extent and type of soil manipulation imposed on the field – usually with more soil work resulting in a loss of soil structure. The four soil properties are also integrally related with each other in interesting ways.

However controllable or uncontrollable these soil properties may be, the quality of the soil and field depends on the farmer maintaining some level of stewardship in his field work. Degradation of the soil can cause deterioration of the soil's ability to not only provide a good quality medium for crop growth, but also to lessen the soil's ability to resist soil deformation and pressure transfer to deeper levels of the soil profile. This loss of resiliency could harm not only the farmer's yield and future cropping levels but any buried archaeology (a historical resource) that exists within the soil.

It is important that these key parameters affecting soil sustainability are monitored and cared for during field operations. Currently, it is not exactly known how differences in cultivation methods or field operation regimes might affect buried artefacts, but it is obvious that an applied interest in long-term profitability and soil health would have extended effects, one of which would include enhanced protection for buried artefacts.

2.4 Perceived opportunities for further investigation

This literature review and concurrent discussion about the factors involved in buried artefact damage in cultivated soils highlights some knowledge gaps and research areas open for further study.

1. Lack of literature relating to buried artefact damage by pressure transfer under field operations:
    a. There is a lack of quantified information on the indirect damage to buried artefacts by agricultural operations.
        i. Researchers and archaeologists alike agree that there is a need for experimental studies using rigorous methods, collecting sound data within real and experimentally-created situations. At this time, the knowledge gap exists at an international level.
2. Indirect damage mechanism is not quantified in literature:
    a. Many archaeological surveys and case studies have been able to document plough / tillage implement direct damage to buried artefacts, through direct physical contact between a tillage tool and an artefact. While case studies and surveys are not considered experimental, they do provide information that may be evaluated. While indirect damage, seems to have been overlooked, it does seem to be a large part of the buried artefact damage issue.
        i. The indirect type of damage would be primarily caused by soil-surface loading, generally delivered by field operations, subjecting buried artefacts within the soil profile to the application of relatively high levels of subsurface pressure. An artefact buried within the plough layer could be subjected to the direct damage caused (for example) by a plough share; however, artefacts located deeper than the reach of the plough blade remain at risk.
        ii. This type of damage may have been overlooked simply because it is a less visible and less extreme form of artefact damage. The concern is that indirect damage from pressure transfer is still able to cause an entire ceramic pot to shatter, or crush a human bone, scenarios which would irreversibly deplete the buried historical record.

Investigation is required to fill these existing research gaps. The undertaking of such research would require extensive experimental work in both a controlled laboratory as well as in a field environment.

1. The subsurface pressures at which buried artefacts break needs clearer definition. Since there are many types of artefacts existing in cultivated soils across England, a few basic artefact types must be chosen to represent larger classes of artefact types. The chosen artefact type(s) would need to represent artefacts that would be most vulnerable to in-field damage.
    a. Ceramic-type artefacts would be a useful study material, as the human societies tend to use ceramic in most historical periods, and thus a large amount of

information can be gained from studying ceramic artefacts. Ceramics, being thin and brittle, are also easily damaged or broken in their buried state.

b. Bone artefacts, especially human bone, would also be an appropriate study material. Archaeologists can discover much information from human skeletons, and if the fragile bones are damaged or destroyed in their buried state, this information becomes lost.

2. The type of subsurface pressure magnitudes being generated under contemporary field operations within cultivated soil should be quantified.

   a. Understanding the individual and cumulative effects that both farming operations and cultivation methods have on the soil medium is important for the evaluation of how buried artefacts behave *in situ*.

Once the breakage point and characteristics of chosen types of buried artefacts have been quantified, and these breakage points correlated to subsurface pressure magnitudes, breakage thresholds can be evaluated relative to field operations.

Correlation of the surface loading and the subsequent effects on buried artefacts will yield a better understanding of the issues surrounding buried artefact breakage in cultivated soils, and will enable strategies for the protection and mitigation of the buried historical resource on both national and international levels.

Chapter 3: Buried Artefact Breakage Laboratory Trials

3.1 Introduction

This work has focused on the indirect damage caused by pressure transfer to buried ceramic artefacts. The investigations explored the potential effects that subsurface pressures generated by soil-surface dynamic loading (*i.e.*, farm tyre/track-supported operations) have on buried ceramic pseudo-artefacts and real aged, non-stratified, and non-collagenous human bone artefacts. This chapter describes experiments conducted to estimate the magnitudes of subsurface pressures that correspond with buried artefact breakage. Threshold peak subsurface pressures were then correlated to peak subsurface pressures collected under field operations, making it possible to define which field operations might or might not break buried artefacts in a cultivated field.

This investigation used replicate ceramic pots to simulate real ceramic artefacts. The pots were crafted for the project by Andrew McDonald, a specialist in pottery reproductions. More information about the pot reproduction process is described below.

The real aged, non-stratified, and non-collagenous human bones were medieval human radii bones excavated by archaeologists at the Wharram Percy Medieval Village site. The bones were donated to the project by Simon Mays of English Heritage (human skeletal biologist; Portsmouth, England).

3.2 Methods

3.2.1 Pressure sensing

Ceramic strain gauge pressure transducers were used for the subsurface pressure sensing aspect of this work (Figure 3.1). These sensors are of robust, waterproof, construction and thus durable enough to withstand the rigors of this research.

These sensors were produced by Roxspur specifically for this project, as a simpler, modified version of model #M6420-92. Manufactured to industry standards, they can sense applied pressures up to 10 bar (1.0 bar = 14.5 psi = 100.0 kPa). The minimum sensitivity, or electrical resolution, of the sensors was 0.0007 bar. After considering steady state noise in the data recording, a realistic minimum sensitivity was found to be ~ 0.02 bar.

The pressure transducers were mounted into aluminium cylinders (Figure 3.2), since they were considered to be relatively small compared to the buried objects being tested within this study. Once mounted, the sensors were calibrated using an air pressure system of calibration (Dain-Owens, 2006).

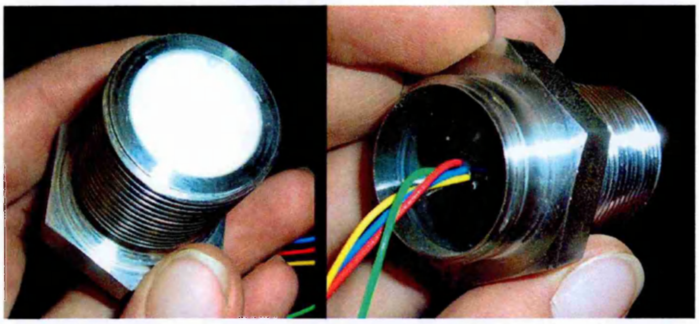


Figure 3.1: Strain-gauge ceramic pressure transducer used for the studies.

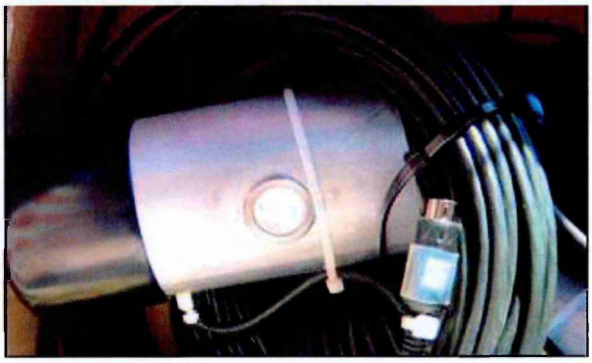


Figure 3.2: Pressure sensor mounted in the aluminium cylinder.

The ceramic membrane pressure sensors (19 mm diameter, 10 bar limit) were mounted into an aluminium cylinder of dimensions 20 cm length, 7 cm diameter. Aluminium was chosen as it has a similar modulus of elasticity to common ceramic materials (Gordon, 1991). The sensors were calibrated with compressed air, and referenced to a traceable dead weight pressure standard.

Before the soil bin laboratory trials, the sensors were randomly buried along the central axis of the soil bin (alongside the buried pots and bones) under 250 mm of soil. Small pits were dug vertically down into the soil, backfilled carefully with recompaction in layers to assure that the bulk density of the soil was the same as the undisturbed soil. After burial, the sensing system function was double-checked.

3.2.2 Handmade ceramic pot burial

Pottery specialists at Oxford Archaeology selected four different types of generic pottery styles and tempers, representative of different common pottery types found on UK archaeological sites of different periods.

The four pot types are shown in Figure 3.3, with the following descriptions.

Figure 3.3: Four types of the handmade ceramic pots used in the breakage trials.

Left to Right, Top to Bottom: Shell Tempered Late Saxon St Neots type cooking pot, Grog tempered generic beaker (grog is previously-fired, ground-up bits of ceramic material from earlier, unsuccessful attempts at making the same vessel), Flint tempered bead rimmed jar, Quartz tempered generic narrow mouth jar.

Grog tempered generic Beaker

An early Bronze Age Beaker was selected to represent low fired, hand-made pots typical of the early prehistoric period. In archaeological contexts this pot is particularly fragile. It is often found in burial contexts as a complete vessel, or as a 'placed deposit', consisting of an intact vessel which would have been deliberately buried as a symbolic act (Oxford Archaeology, 2008).

The replica Beaker pots used within the experiment were hand built using the coil method, and fired to a low temperature of 700 degrees Celsius in order to replicate original conditions of production. The pots were made using a grog temper consisting of previously-fired, ground-up bits of ceramic material from earlier, unsuccessful attempts at making the same vessel.

Flint tempered bead-rimmed jar

The bead-rimmed jar was selected to represent the hand-made pot fired at higher temperatures, commonly flint tempered, dating from the middle to late prehistoric periods. These pots are generally found in domestic assemblages and were used as storage or drinking vessels (Oxford Archaeology, 2008).

These pots were coil-built and fired to 800 degrees Celsius, slightly higher than is believed to be typical for this type of pottery. A higher temperature was used, as the flint inclusions caused the pot to crack when fired at low temperatures. The pots survived firing when the temperature was raised and the flint content decreased. The end product was slightly more robust than originally intended, and was thus more representative of the later, rather than the middle prehistoric period.

Quartz tempered generic narrow mouth jar

The quartz tempered jar was selected to represent the type of mass produced wheel-thrown pottery increasingly produced by specialist potters (as opposed to pot-making in domestic contexts) throughout the later prehistoric and historical (particularly Roman) periods. The use of a pottery wheel and the development of kiln firing allowed pots to be consistently stronger. This is a style of pottery frequently recovered within domestic contexts, from a wide range of different periods (Oxford Archaeology, 2008).

The pots were wheel-thrown and fired to 900 degrees Celsius using a fine quartz (sand) temper. The finished pot was consistent in its characteristics, robust and shared a good likeness to originals found in excavations.

Shell tempered Late Saxon St. Neots type cooking pot

The shell tempered pot was selected to represent generic, domestic cooking pots of the later historical periods. They are less common at archaeological sites than other pottery types, but represent an important type of pottery found in many significant archaeological contexts (Oxford Archaeology, 2008).

The pots were wheel-thrown and fired to a temperature of 900 degrees Celsius using a shell temper of up to 0.01 m in size, consisting of crushed marine shells (oyster). Once again a higher firing temperature was needed than was originally planned, in order to maintain pot stability. The end product was a moderately robust pot that adequately represented the material it was attempting to replicate.

For the production of all of the replica pots, a generic modern potters-clay was used. Therefore the differences in pot characteristics derived from using different tempers, pot construction and firing temperatures/techniques, and not from differences in indigenous English clays.

Before burying the pots in the soil for the breakage trials, the pots were instrumented with an electrical system that would enable *in situ* (buried) breakage detection (Dain-Owens, 2006). This instrumentation consisted of two painted-on, silver conductive traces that would form an electric circuit around part of the pot. This electric circuit remains closed and connected as long as the pot is intact. When a subsurface pressure is applied onto the pot and fracture occurs, the conductive trace is broken. The conductive circuit was connected via wires running from the buried pot to a circuit board, to a data logging system, which recorded when the circuit broke. This breakage detection system was based on the instrumentation used in Dain-Owens, 2006; however some improvements and modifications were made to adapt the system to objects having more surface variation.

Each conductive trace was painted around a pot in a specific pattern to form a continual circuit that broke with the pot. The pot orientation and shape had been found to dictate specific circuit pattern and trace placement (Dain-Owens, 2006). In this study, the application pattern of the conductive trace was the same on all pots because they were all buried in the same horizontal position. This orientation was used as it was previously found to be the weakest position in previous pilot studies (Dain-Owens et al., 2007).

Within these trials, one conductive trace was placed around the top rim of the pot (with three loops in the circuit – one on the inside of the pot rim, one on the top of the pot rim, and one on the outside of the pot rim, all within the same circuit trace). A second trace was painted in a sinuous circuit around the body of the pot. See Figure 3.4 for images of how the pots were instrumented.

Figure 3.4: The instrumented pots, pre-burial.

The top left photo shows the conductive trace before wire attachment; the top centre photo is of the same pot after wire attachment. The middle left photo is of all four types of pots after instrumentation was completed. The top right, middle right, bottom left and bottom right photos are close-ups of the quartz tempered, the grog tempered, the shell tempered, and the flint tempered pots (respectively) after instrumentation.

Since the pots used in this study were handmade, with many irregularly-shaped inclusions mixed into a porous medium (clay), the ceramic surface was not entirely suitable for the application of the conductive traces. In pilot studies with modern terracotta pots the ceramic medium was denser and more homogeneous; thus, a thin coating of clear lacquer was applied, after which the conductive trace was applied without difficulty. With these handmade pots however, the clear lacquer was not enough. In order to patch up the pots' surfaces a yellow acrylic paint was applied. The paint was of a viscous consistency, thus it was easy to apply with a small toothpick-sized plastic palette knife to fill in the holes and cracks as necessary. This ensured that once the conductive trace was painted onto the pot, it would provide a continuous circuit (see Figure 3.5). It should be noted that the acrylic paint did not affect the strength of the pots in any significant way. It will be seen in the results that the breakage patterns in the pots were not influenced by the applied spots of the acrylic paint as a filler material.

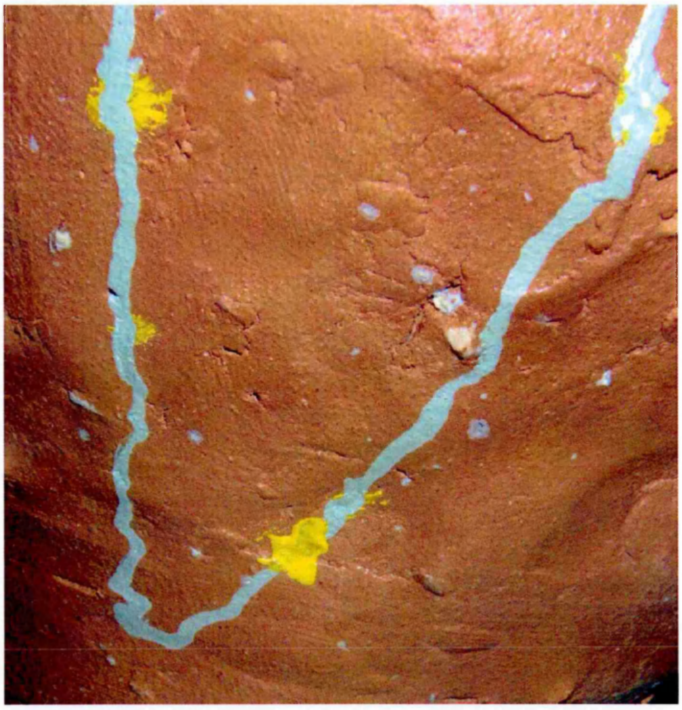


Figure 3.5: Application of yellow viscous paint with the conductive paint.

This allowed cracks and other irregularities in the pots' surfaces to be filled in that would otherwise inhibit the continuity of the conductive trace.

The burial of the pots was done very carefully. The pots were buried in the horizontal position (on their side) with their vertical axis positioned perpendicularly to the tyre's path of movement (Figure 3.6). The pots were buried at a topmost depth of 250 mm, around the depth of the plough layer in a field soil. The pots were buried horizontally just under the plough soil depth to simulate a 'worst-case-scenario.' If a pot was buried in the field higher than 250 mm deep, it could be directly hit by a plough or other agricultural implement. If a pot is under the plough layer, it will not be susceptible to direct damage but could still be damaged by pressure transfer and soil deformation from surface loading.

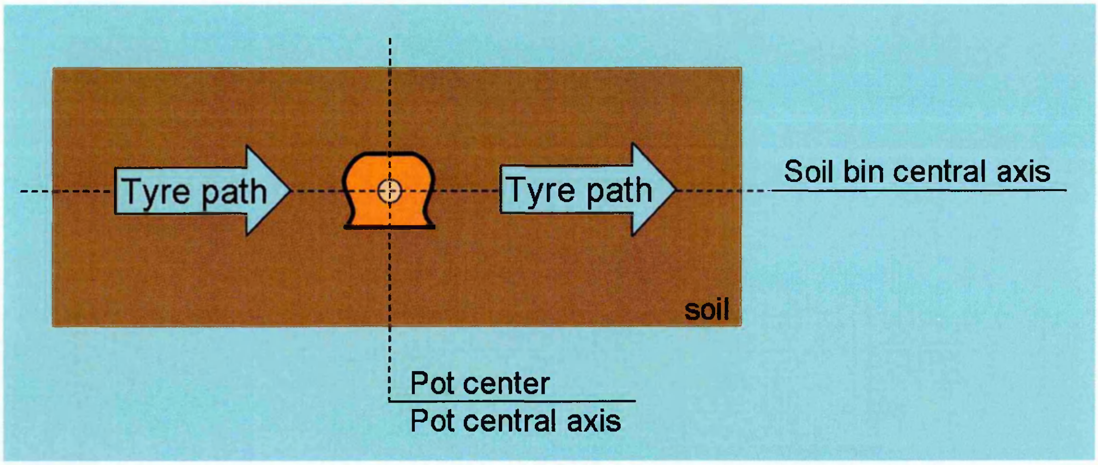


Figure 3.6: Schematic diagram showing pot orientation relative to the tyre path.

The pots were buried as follows. A pit was dug in the centre of the soil bin, to a depth of 250 mm plus the width of the pot. The instrumented pot was filled with soil, which was packed in to ensure that the contents of the pot were at a similar bulk density to the soil around the pot. The pot was placed into the hole so that the centre of the pot was on the central axis of the soil bin. The hole containing the prepared pot was refilled with soil. It was important that the soil was packed carefully in layers around the pot. This was to ensure the soil around and above the pot was at a similar bulk density to the rest of the soil in the soil bin (1.4 g/cm^3 surface to 250 mm deep; 1.6 g/cm^3 deeper than 250 mm). There was usually some soil leftover, which was expected, as the ceramic material of the pot will have displaced a small amount of soil.

Once the soil was packed in layers back into the hole, the surface of the soil was levelled off so that the tyre would have a flat and smooth surface to roll over, thus eliminating any variability in depth that could have been introduced into the experiment. See Figure 3.7 for some photos showing the burial of a pot in the soil bin according to the method outlined above.

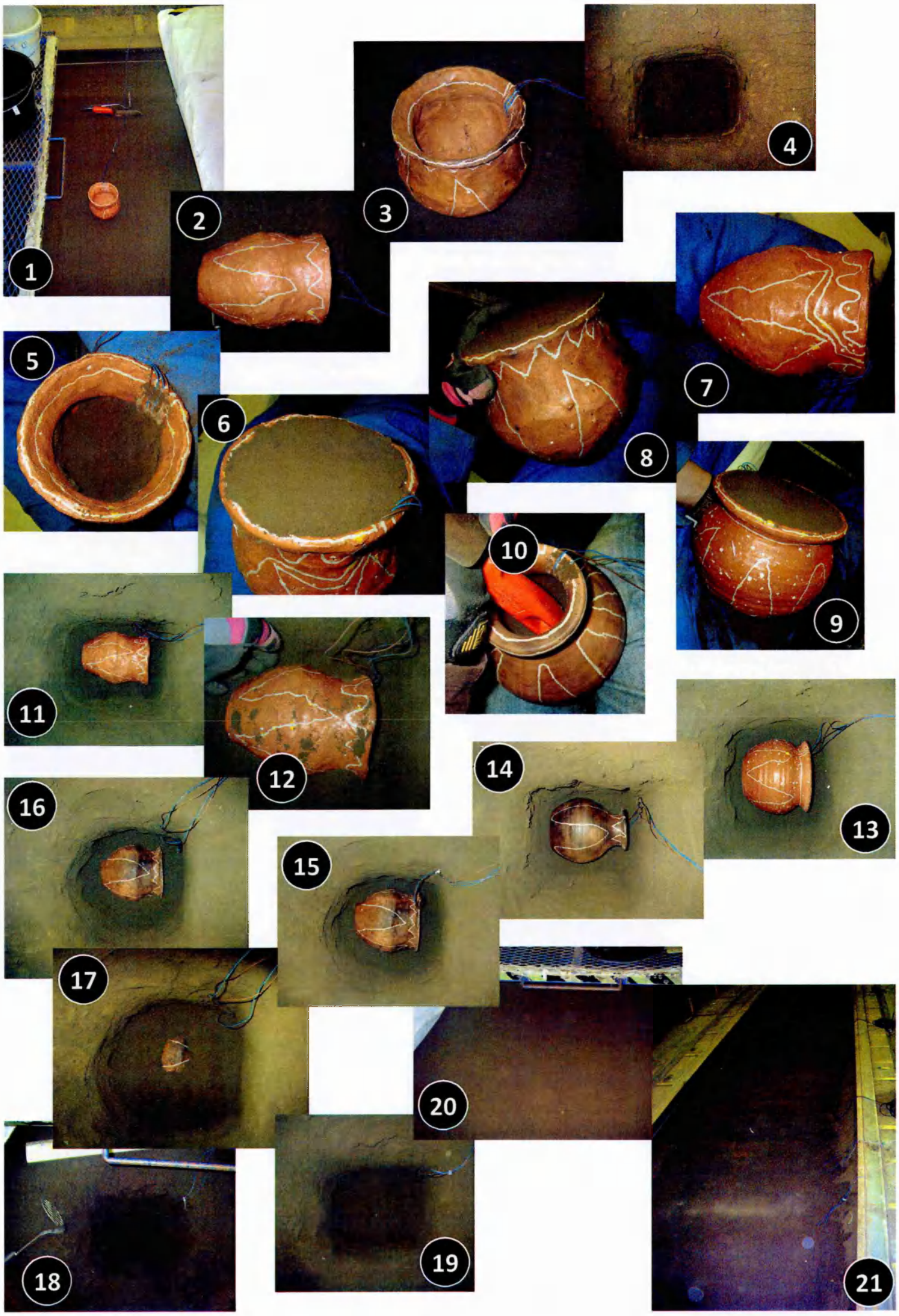


Figure 3.7: The process of pot burial.

The following descriptions relate to the numbered images in Figure 3.7:

(1) shows a section of the soil bin before pot burial;

(2-3) show pots before burial;

(4) shows the hole, dug carefully to a size slightly larger than the pot, and to the depth that the pot, when placed inside the hole, would have a topmost depth of 250 mm;

(5-7) show the filling of the grog tempered pot, with 7 showing how the pot would be placed in the hole before burial;

(8) shows the flint tempered pot, filled with compacted soil;

(9) shows the shell tempered pot filled with compacted soil;

(10) shows the quartz tempered pot in the process of filling. For this pot, the handle of the trowel was useful in compacting the fill soil in layers, as the neck of the pot was not wide enough for a hand to fit through;

(11-12) show the grog tempered pot placed in the bottom of the hole, with the soil being packed in around it in layers;

(13-15) shows the shell tempered, quartz tempered, and flint tempered pot respectively at the bottom of their holes, before refilling;

(15-17) show the flint tempered pot at the bottom of the hole, as the soil is gradually filled in and compacted in layers around the pot;

(18-19) show the hole after the pot has been covered with soil, gradually filling up with soil as the refilling and compaction in layers continue;

(20) shows the hole after the refilled hole has been levelled off to match the surface level of the rest of the soil bin;

(21) shows the entire soil lane after all sensors, pots, and bones have been buried prior to a trial.

The results of the soil bin pot breaking experiment were not easy to predict, but it was understood that the main parameters determining the pot breakage thresholds would be pot size, shape, and material strength. The bigger pots were expected to break more easily and under lighter loads; the smaller ones less so, and under heavier loads. The pots that were fired at a lower temperature and that had larger temper inclusions were expected to break under lighter loads; the pots fired at higher temperatures and with smaller pieces of temper were expected to break later, under heavier loads; this is demonstrated and discussed within the discussion chapter (Chapter 6).

3.2.3 Human Bone Burial

The decision to use human bones in addition to ceramic pots in this study was made at an early stage in the project. It was not however, a decision made easily, and it involved much ethical discussion.

This project had an end goal of helping archaeologists and land managers to preserve and mitigate damage to buried artefacts. The value of buried artefacts generally lies in the information that can be gleaned from them by trained experts (archaeologists, anthropologists). Artefacts potentially contain clues to a variety of aspects of culture and society during their original period of use. Information can come from any material artefact; however, no other artefact can give as much insight into a person's life as human bones. Animal bones yield information about human settlements and give more clues to the society's status, general wealth, and general occupation, but they do not provide information intrinsically connected to people (as previously described). Bones from a cow will not answer why its owner died or the owner's age, for example. For this reason, human bones are given more protection relative to other artefact types.

A trained archaeologist deciphering a human bone can determine whether the person was male, female; young or old; if they had any terminal illnesses or other disease; if they suffered from malnutrition or were healthy; their social class; their occupation (depending on what the occupation was); and sometimes even the cause of death. More information related to society type and size, and time period can be gained from looking at whether bones are found on their own, in a group of burials, or a mass burial, as well as by looking at the position of the deceased in burial.

This project took all of the above information into account when deciding whether or not to use human or animal bone. Since there was no previous research relating to damage to human bones in cultivated or actively managed fields, there was no existing information upon which to base a management strategy that would protect these buried bones.

The need was thus evident to investigate damage to buried human bones in actively managed or cultivated soils, and as this project had the resources to address this problem, the decision was made to include a small study using relatively non-valuable human bones to get a preliminary idea of what was happening to the human bone artefact-type under soil submitted to dynamic surface loading.

The specific bone-type used in this study was the human radius bone. A set of 10 radii bones were provided by English Heritage for buried breakage testing. All bones were from the Wharram Percy Medieval Project Site, a medieval village in Yorkshire, England that has been extensively excavated and catalogued by archaeologists. Figure 3.8 shows some of the medieval skeletons unearthed at Wharram Percy. Figure 3.9 shows the English Heritage bone collection from which the bones came for use in this study.

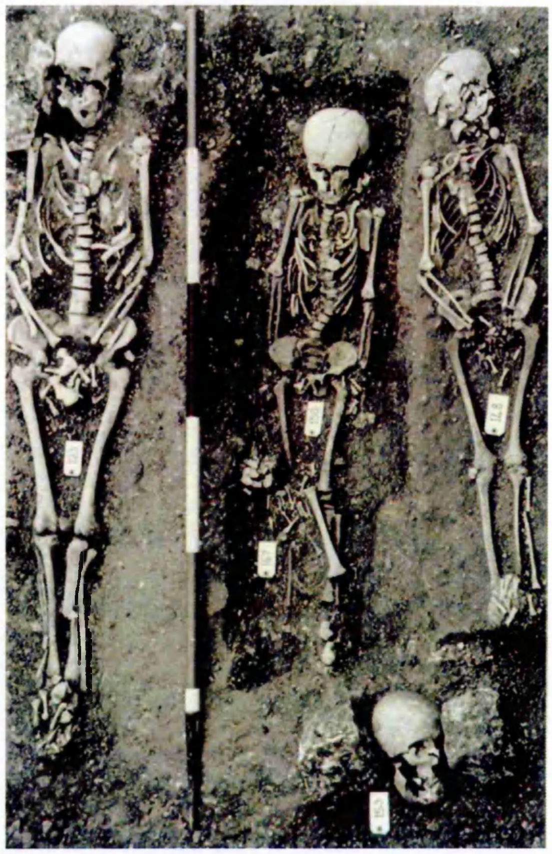
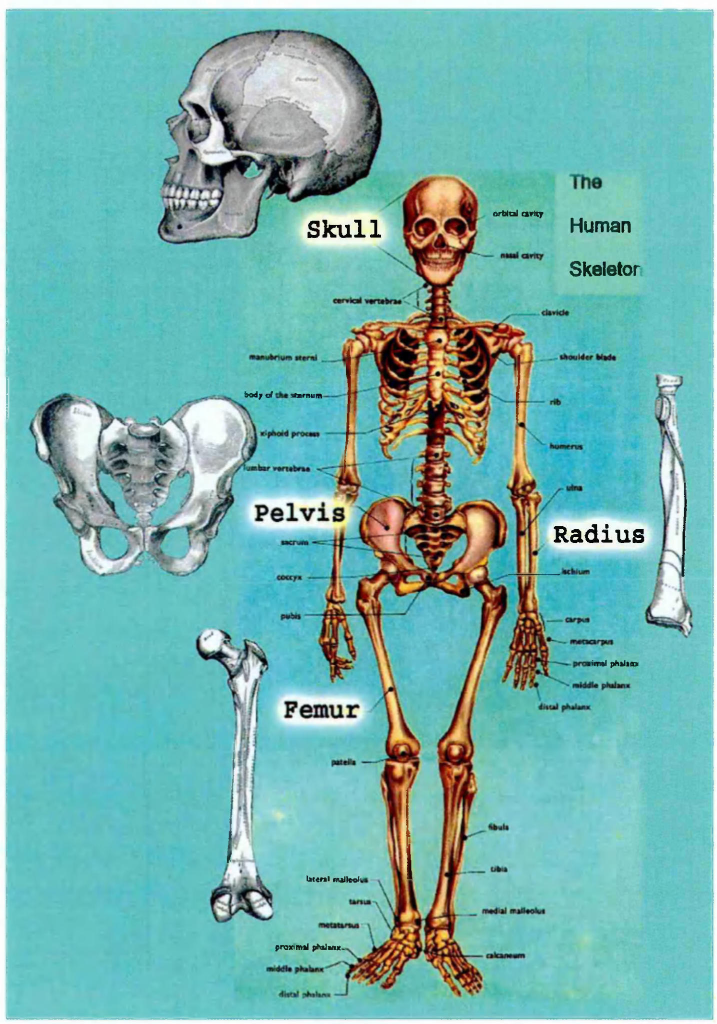


Figure 3.8: Medieval Skeletons found at the Wharram Percy Project Site.

Figure 3.9: English Heritage Archaeological storeroom in Portsmouth, England.

Unrecorded, stray bones from the Wharram Percy Project were loaned for use within the Trials project; the bottom photo of radii bones in plastic bags show the borrowed collection.

The radius bone-type was chosen because it is less valuable relative to other considered bone types (skull, pelvis, and femur). See Figure 3.10 for a human skeletal diagram. It was also a simple bone shape, reducing the variables affecting bone breakage. Radius bones were numerous in the collection of bones available to the study from English Heritage's Wharram Percy Project. It was also a weaker bone (shorter, thinner) than the femur, allowing the study to evaluate breakage of a bone-type that was of relatively average and middle-strength (weaker than a femur, stronger than a rib), making this small study more representative of in-field buried bones.



Not to scale

Figure 3.10: Human Skeleton with inset images of the bone types considered for this project.

New image constructed from different sources, including Grey's Anatomy 20th U.S. edition of Gray's Anatomy of the Human Body, originally published in 1918 and therefore lapsed into the public domain.

The radii used for the project were exclusively un-stratified, meaning that they were of less value to archaeologists, as they could not be connected with a particular skeleton, family plot, or particular time period upon excavation. The bones used were all old enough to have lost the collagen inherent to any live and recently live bone. This meant that the bones would not have elastic material strength properties. They would not bend in breakage tests; as without any collagen they become brittle. The bones were evaluated visually and found to be in good condition, without any pre-existing cracks or damage. They were confirmed to be 'average' bones free of disease by Simon Mays, the English Heritage human skeletal biologist based in Portsmouth. The bones in this study were probably of mixed male and female origin, but were all adult bones, similar in size.

The brittle property of the bones was particularly important to this study. Brittle bones are much more delicate and fragile than fresh bones. Without the collagen, bones lack the ability to absorb some of a load by deflection (strain), and instead will crack and break at a lower load threshold. Over time, bones naturally degrade and lose collagen. This study used non-collagenous bones in order to best represent bones buried in actively managed fields and land.

With a chosen bone type and a set of quality-selected medieval non-collagenous human radii to study, the burial and test methods implemented in pot testing had to be adapted for bone testing. The same burial depth was used (250 mm topmost depth); and instead of investigating the effect of bone type (similar to the study on pot type), the bone orientation relative to the tyre path was explored.

It should be noted that since the bones were not symmetrical, their position in the soil as well as their position relative to the path of surface loading had to be specified. It was decided that all bones would be buried dorsal-side-up, as if the bone was connected to a human arm positioned palm-down on the flat soil surface.

It was also decided to test the radii bones at two orientations relative to the oncoming surface load because little was known about how they would break, and simply testing the bones in both orientations would yield more information about buried bone breakage. The bones were split into two groups, each orientated in one of two positions, either perpendicular or parallel to the path of surface loading. Each trial within the study would thus include one bone orientated perpendicular to the tyre path, and one bone orientated parallel to the tyre path (two bones per trial). The perpendicular orientation was estimated to be the worst case scenario for the bone, as it placed the bone's centre in a position where it might bend the most and thus be in high tension from a tyre surface load. The parallel orientation was estimated to be less damaging to the bone, however it was estimated that this orientation was the most likely to yield crushing bone failure. See Figure 3.11 for a schematic diagram of the buried bone orientations.

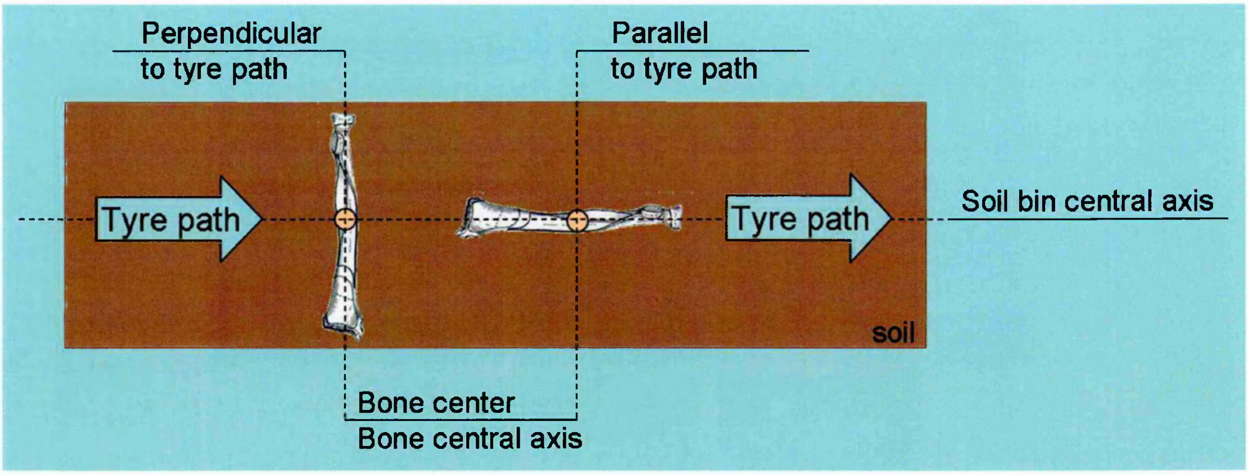


Figure 3.11: Schematic diagram showing the orientation of the bones relative to the tyre path.

The instrumentation for the bones was similar to that of the pots (see Figure 3.12). Two conductive trace circuits were created, one on the top side and one on the bottom side of the bone. The top trace would detect breakage of the bone from failure in compression, and the bottom trace would detect breakage of the bone from failure in tension.

The paint was applied in a line, from one end of the bone to the other. Since the bone was of a linear shape, there was no need for sinuous curves or other paint patterns. The wires connecting the painted conductive trace to the data logging system were attached at the ends of the bone, where they would have the least affect on the breakage dynamics of the bone.

Since the bones were old, and collagen degradation had taken place, their surfaces were not entirely smooth (especially at the ends). While there was a thin coat of moisture resistant lacquer sprayed over the surface of the bones before the conductive trace was applied, there were still porous areas. For this, the yellow viscous paint was used to patch over and provide a smooth surface for the conductive paint. Another coat of lacquer was sprayed onto the instrumented bones to protect the instrumentation from moisture in the soil. The circuit was tested before the bones were buried for testing.

Figure 3.12: Bone Instrumentation:

The top left photo shows two radius bones, the conductive trace pen, and the yellow acrylic paint. The other images show wire attachment points and general views of instrumentation.

The bones were buried by the following generic method. A pit was dug in the centre of the soil bin, to a depth of 250 mm plus the measure of the width of the bone. Depending on the orientation treatment, the hole dug was either perpendicular or parallel to the tyre path. The instrumented bone was placed in the hole so that its centre was on the central axis of the soil bin. A level was used to check that the bone was lying flat in the hole, so that one side was not higher than the other causing different breakage dynamic. The hole containing the prepared bone was refilled in the same manner as the pots, with soil, packed carefully in layers around the bone.

Once the soil was packed in layers back into the hole, the surface of the soil was levelled off so as done for the pot burial. Figure 3.13 shows the bone burial process.

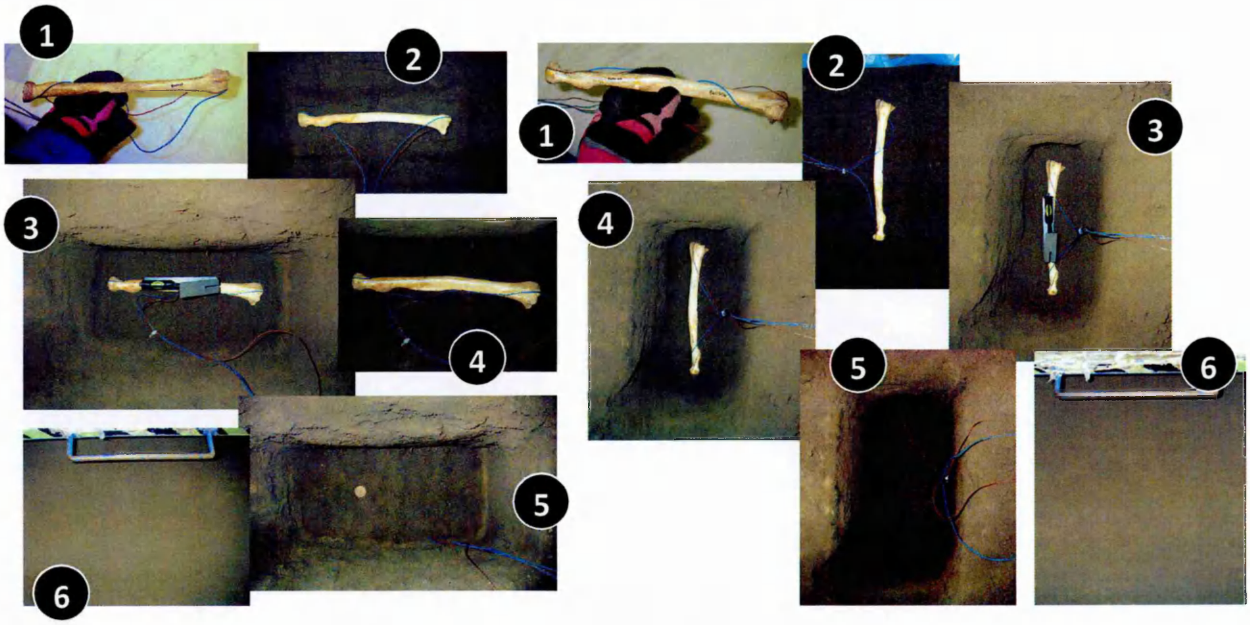


Figure 3.13: The process of bone burial.

The following descriptions relate to the numbered images:

(1) Shows the bones used in one of the trials for both orientations (perpendicular and parallel to the tyre path). The bones were prepared and instrumented, and just before burial the conductivity of the trace was double-checked. The bones for both orientations were treated exactly the same during the entire trial, the only difference was their orientation in the soil.

(2) The bones were placed in the soil bin at the proper location. The line was drawn in the soil, matching the size and shape of the hole necessary for the bone.

(3) These images show the dug hole, with the bone placed inside. The device resting on top of the bone is a levelling device. This was used to ensure that the bone was resting flat, and not at an angle that might affect its sensitivity to surface loadings. The level of the top of the bone was also measured (not shown) to ensure that it was buried at a 250 mm topmost depth.

(4) These images show the bone before the hole was filled in. Soil around the bone was pressed in very carefully while measuring for level and depth, so that the bone would not be affected by soil movement during hole refilling.

(5) These images show the hole mid-refilling. The soil was backfilled in shallow layers very carefully, so as not to change the level or orientation of the bone and so as not to damage the bone before the trial.

(6) These images show the surface of the soil after the bones have been successfully buried.

The strength of the bones was not known. There is much literature about the biomechanics (and thus material strengths) of live or recently deceased bone (i.e., bone still containing collagen). This data could not be related to this study however, because bone with collagen has very different mechanical properties. It is flexible and has strain rate properties that make it bend and stretch relative to how fast or slow any loading is applied. The aged, non-collagenous bone from the medieval period used in this experiment was entirely brittle in its mechanical properties. Indeed it may be seen to have mechanical similarities to the ceramic material of the pots tested within this study.

An unknown factor was the strength of the bone material relative to the strength of the ceramic material of the pots. Although the materials were both brittle, bone has a laminate structure, which strengthens it even when its flexible component has degraded away. The shape, and internal structure, also has an effect on the breakage dynamics of the bone. The bone has a rod-like shape, while the pots have a cylinder-like shape. If the two objects were made of exactly the same material, but retained their different shapes, they would still break differently when buried and subjected to surface loading.

In summary, it was not possible to predict how the bones would break (or even if they would break). If either orientation of the bone was to break, it was thought that it would be the perpendicularly-orientated bones. It was estimated that the bone would have a clean break perpendicular to the proximal-distal axis of the bone. There was also the possibility that the ends of the bone would be crushed (as their structure was different from that of the central length). There were hypotheses that the bone parallel to the tyre path might not break in the middle, but rather the ends or the entire bone might get crushed under the dynamic surface loading.

3.2.4 Soil bin laboratory trials

Five trials were conducted in the soil bin laboratory see Figure 3.14 (Godwin et al., 2006). The trials involved pressure sensors, handmade pots, and radius bones, buried at a topmost depth of 250 mm in a sandy loam soil. The methodology of the laboratory trials is explained in this section.

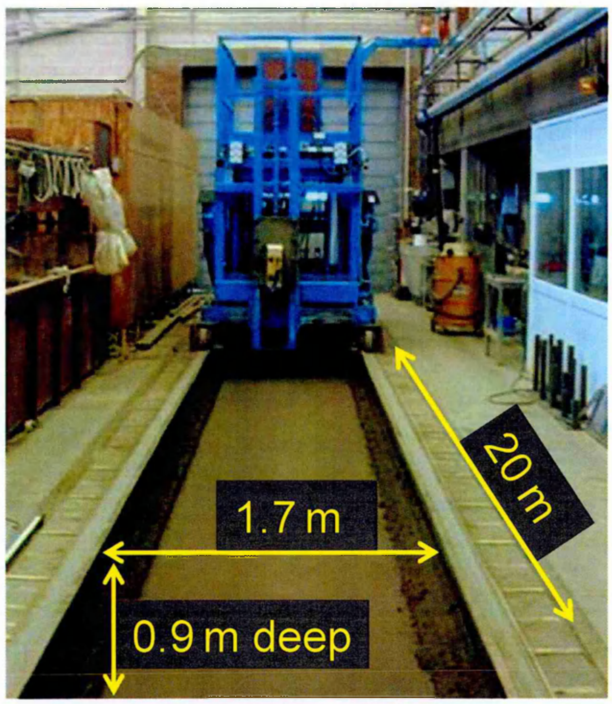


Figure 3.14: Soil bin and soil processor with dimensions of soil lane noted.

The experiment was performed with a sandy loam soil, compacted above 250 mm to 1.4 g/cm^3; under 250 mm depth to 1.6 g/cm^3. Soil preparation was checked with an Eijelkamp penetrometer to ensure that the entire length of the bin was similarly prepared and the possibility of larger scale soil variability affecting the trials was eliminated.

The dynamic surface loads were applied using the 12-tonne load frame described by Ansorge and Godwin (2007) using a similar methodology to that set out in Dresser et al. (2006), whereby an inflated, loaded tyre is rolled over a prepared soil surface at a set speed (7 kph). Within this trial however, only one tyre was utilized; a Trelleborg cross-ply implement tire 600/55-26.5 that had its tread removed by a buffing operation. The use of only one tyre as opposed to a range of various tyres removed a source of variation from the experiment.

The tyre was chosen because of its ability to operate normally at relatively low inflations and loads through to relatively high inflations and loads; thus enabling it to generate a large range of subsurface pressures for the pot breakage trials. Using the tyre manufacturer's chart as a base, a load inflation plan for the successive tyre runs was created, setting the experimental pressure at one tonne less load than in the manufacture load/inflation chart. The use of only one tyre as opposed to a range of various tyres also maximized the study's efficacy.

Within each trial, the tyre was prepared for each run by inflating it to a specific pressure and loading it hydraulically to a specific load. Six runs were performed within each trial, with increasing inflation pressures and magnitudes of load to increase overall surface loading at the soil surface. This generated successively higher subsurface pressures on the buried objects. As the pots were instrumented with a breakage detection system alongside pressure sensors, the pressure at which breakage occurred could be identified.

The tyre inflation pressures and load configurations are presented in Table 3.1.

Table 3.1: Tyre data for all trials

	Run #	1	2	3	4	5	6
Trial Setup	Tyre	Trelleborg Agricultural Cross-Ply Implement Tyre 600/55-26.5 (tread removed by buffing)					
	Pressure (bar)	0.5	1.0	1.5	2.0	2.5	2.8
	Load (tonne)	1.7	2.8	3.8	4.9	5.9	6.5

During the trial runs, a data logging system was used to record the relative resistance for each of the pot and bone circuits. By observing the point at which this resistance changed, the timing of object breakage could be determined while the object remained buried. The output from the buried pressure sensor was also recorded simultaneously. Figure 3.15 contains a schematic diagram of the experimental setup in the soil bin.

The data logger was a FYLDE Mobile Micro Analogue 2 FE-MM8 (Fylde Electronics, Lancashire UK). The data collection for the pot and bone conductive traces was via a direct line passed through the FYLDE unit to enable the relative resistance to be recorded. The sensors' output signal was captured and conditioned using a FE-366-TA Bridge Transducer Module card. This card utilized a dual channel bridge transducer and a strain gauge amplifier. It was capable of conditioning the signal using a filter, a shunt balance, an auto-zero function, and also internal jumpers to set the gain, filter, and bridge type.

Once the tyre runs were completed for each trial, the pots, bones, and sensors were excavated. All events were carefully documented. Documentation included comprehensive photography, measurements of any object sinkage, and notes relating to buried object breakage and fragmentation. This documentation allowed the effectiveness of the conductive trace method to be assessed in addition to enabling the investigation of breakage dynamics.

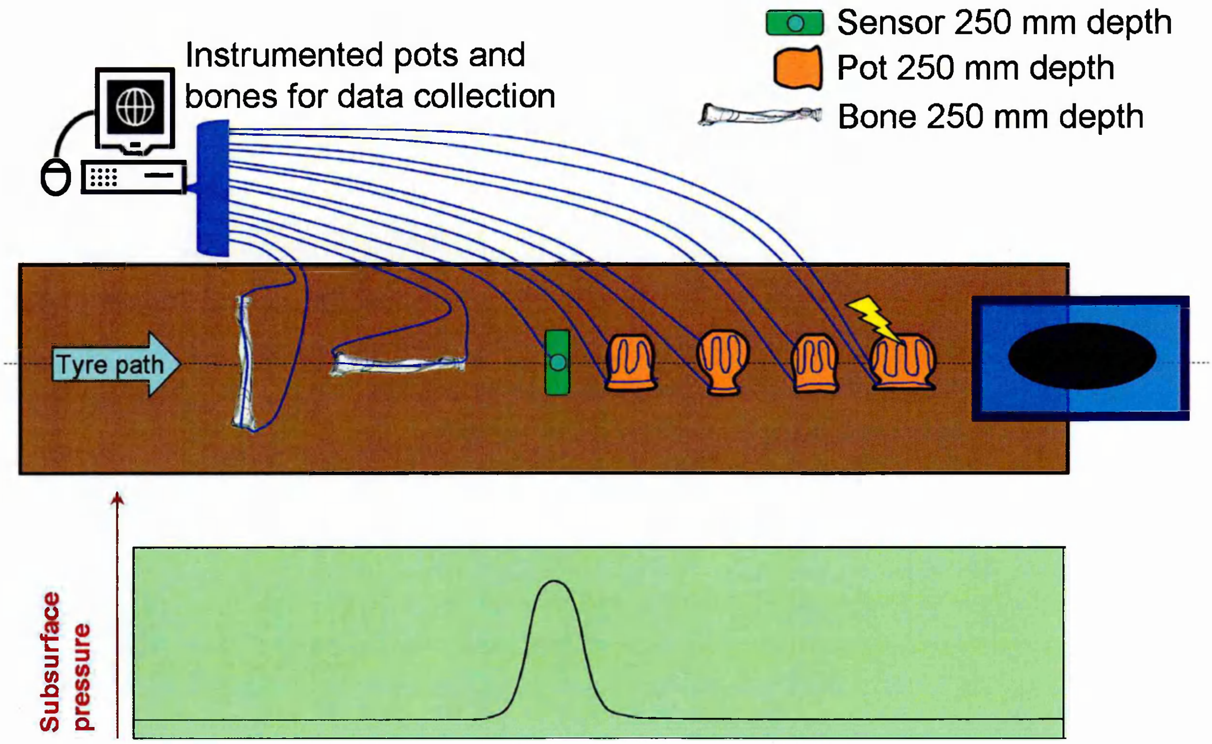


Figure 3.15: A schematic diagram (not-to-scale) showing the soil bin setup (plan view).

The tyre is the source of the dynamic surface loading. The pots (four types) and bones (two orientations) simulate buried artefacts, and the sensors provide subsurface pressure data. The computer data input is shown with the conductive trace instrumentation on the buried objects. A sample subsurface pressure chart is shown for visualization purposes.

Initially, an analysis of variance (ANOVA) was carried out to confirm that the pressures measured in the soil were different from each other and responded to the surface loading by increasing under progressive loading cases. Then, further data analysis consisted of a regression of the peak pressures recorded by the pressure sensors during each run with the first breaking point of each pot type and bone orientation recorded by the buried object's conductive traces.

3.3 Breakage Trials Results

The trials had two types of data output. One was the subsurface pressure output from the buried pressure sensors. The other was the breakage data collected from the pot and bone instrumentation system.

The subsurface pressure data were recorded, and the peak subsurface pressures were extracted from each sensor per run. Originally four pressure sensors were used, and their outputs were analysed using ANOVA to check that they were performing correctly. Two of the sensors proved unreliable, as their pressure data were significantly different from the other two sensor outputs. The outputs from the two sensors with inconsistent data were removed from the remaining analyses, and the two sensors shown to be performing consistently were retained. Thus, the results include two pressure sensors' data from all five trials.

Figure 3.16 shows the magnitudes of the subsurface pressures generated in the soil bin laboratory trials. The mean subsurface peak pressure values for each run (per each load-inflation case) are all significantly different from each other with a mean pressure difference of 0.65 bar. The measured subsurface pressures shown here are the result of the inflation pressure and load of tyre used for applied surface loading, and are therefore higher than the specified tyre inflation pressures (Table 3.1).

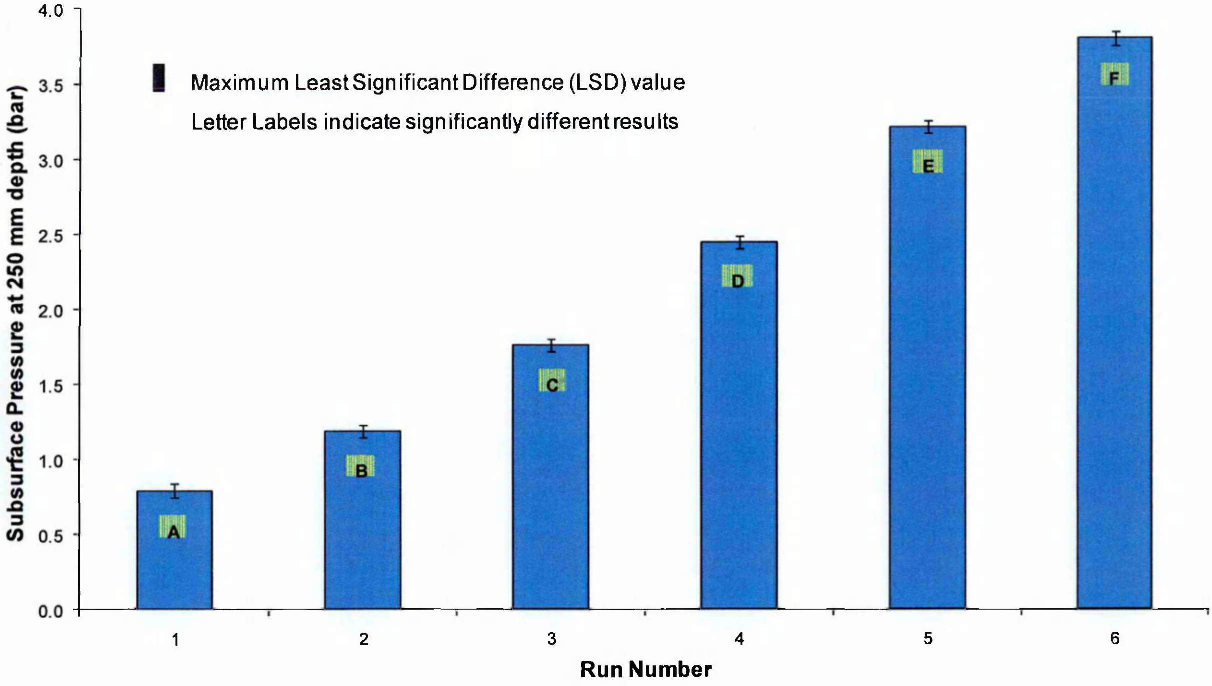


Figure 3.16: Mean peak subsurface pressures from soil bin trials using replicate artefacts.

Statistically analyzed for variance (the data was arranged in blocks by 'Trial', while the treatment tested for was 'Run' in the statistical analysis design) (see Table 3.1).

The pot and bone breakage data are summarized in Tables 3.2 and 3.3, respectively. The objects are listed in ascending order of breakage. It should be noted that the rim of every pot type broke either at the same time or before the body of every pot type. Also, the bottom of bones broke at the same time as the top of the bones, except in one run, where the bottom broke but the top one did not. The Shell Tempered pot can be viewed as the most fragile pot, as it failed during Runs 2 and 3 in the 5 trials; the amount of peak subsurface pressure necessary to break it was 1.32 bar. The Quartz Tempered pot was shown to be the strongest pot used in the trials, as it broke only in Runs 5 and 6 of all trials. The Parallel Bone orientation never broke. This indicates that this orientation is much stronger than the Perpendicular Bone orientation. Within the four trials, the Perpendicular bone orientation broke fully twice, partially once, and not at all once.

Table 3.2: Pot breakage data collected from the soil bin trials.

Pot Type	Trace	Breakage Run
Shell Tempered	Rim	2 – 2 – 2 – 2 – 3
	Body	3 – 3 – 3 – 3 – 3
Grog Tempered	Rim	3 – 3 – 3 – 3 – X
	Body	3 – 3 – 3 – 4 – X
Flint Tempered	Rim	3 – 3 – 4 – 4 – 5
	Body	4 – 4 – 4 – 4 – 6
Quartz Tempered	Rim	5 – 5 – 6 – 6 – 6
	Body	5 – 6 – 6 – 6 – 6

Pot types (treatment) are listed in order of observed 'weakest' to 'strongest' pot type. The lowest peak subsurface pressure necessary to break a pot was 1.32 bar for the shell tempered pot rim.

Table 3.3: Bone breakage data collected from the soil bin trials.

Pot Type	Trace	Breakage Run
Parallel	Top	X – X – X – X (never broke)
	Bottom	X – X – X – X (never broke)
Perpendicular	Top	5 – 4 – X – X
	Bottom	5 – 4 – 6 – X

The 'treatment' was the orientation of the bone in the soil bin relative to the tyre path.

By noting the peak pressures of runs within a trial, and the runs in which the pots and bones broke, the pressure and breakage point could be correlated, providing the breakage point thresholds for each pot type and bone orientation.

Following consultation with the statistics team at Cranfield University (Charles Marshall, Pat Bellamy) and with GenStat Technical Support (Roger Payne), a regression was done using a binomial logit statistical analysis (via GenStat for Windows 10th Edition, a statistical data analysis software package: http://www.vsni.co.uk/software/genstat/).

The type of regression analysis is based on survival statistics theory. The data were analysed according to the breakage point of a pot/bone relative to their 'survival' or, non-breakage, up to that point. The analysis included all object breakages (from all runs) and estimated the distribution of breakage for each artefact type. Since the data recorded from the trials were for total breakage of any pot/bone, the inputs to this analysis were either 0% or 100%.

The analysis assessed whether or not a significant relationship existed between the breaking points of the pots/bones and the peak subsurface pressures; *e.g.*, whether or not there was a good correlation between the breakage of any buried object and the pressures recorded at those breakage points. If the variability within a pot type had been too high, the analysis would not have found any significant regression (see Table 3.4 and Table 3.5).

The outputs were regression parameters of slope (β) and intercept (α) for each object. These factors were then used to define a prediction curve. Equation 1 shows the driving equation, with accompanying explanation.

Equation 1

Base equation (one side logit, one side linear):

$\ln(P / (100 - P))$ *OR* $\ln(r / (n - r)) = \beta * \chi + \alpha$

ln = natural log base e

P = object survival proportion (non-breakage; as a percentage)

$P = 100 * r / n$

n = number of objects in each trial

r = number of survivals (number of objects that did not break) in each trial

β *= slope*

α *= intercept*

χ *= peak subsurface pressure*

Prediction equation:

Used to solve for P, using the β (slope) and α (intercept) factors:

$$P = (100*\exp(\beta * \chi + \alpha))/(1+\exp(\beta * \chi + \alpha))$$

Or, in terms of r and n,

$$r = (n*\exp(\beta * \chi + \alpha))/(1+\exp(\beta * \chi + \alpha))$$

The prediction curves are shown in Figure 3.17 and Figure 3.18 (for pots and bones, respectively). This provides a means to link the results of this study to outside data.

The prediction equation allows for thresholds to be calculated for any given peak subsurface pressure. Figure 3.19 and Figure 3.20 are charts that have been created to show where the 80%, 90%, and 100% thresholds lie for the pots and aged bones used in this study. If outside pressure data were to be compared to the resulting breakage threshold found in this study, the prediction equations could be used with any pressure input of χ. The β (slope) and α (intercept) factors used would relate to the pot or aged bone in question.

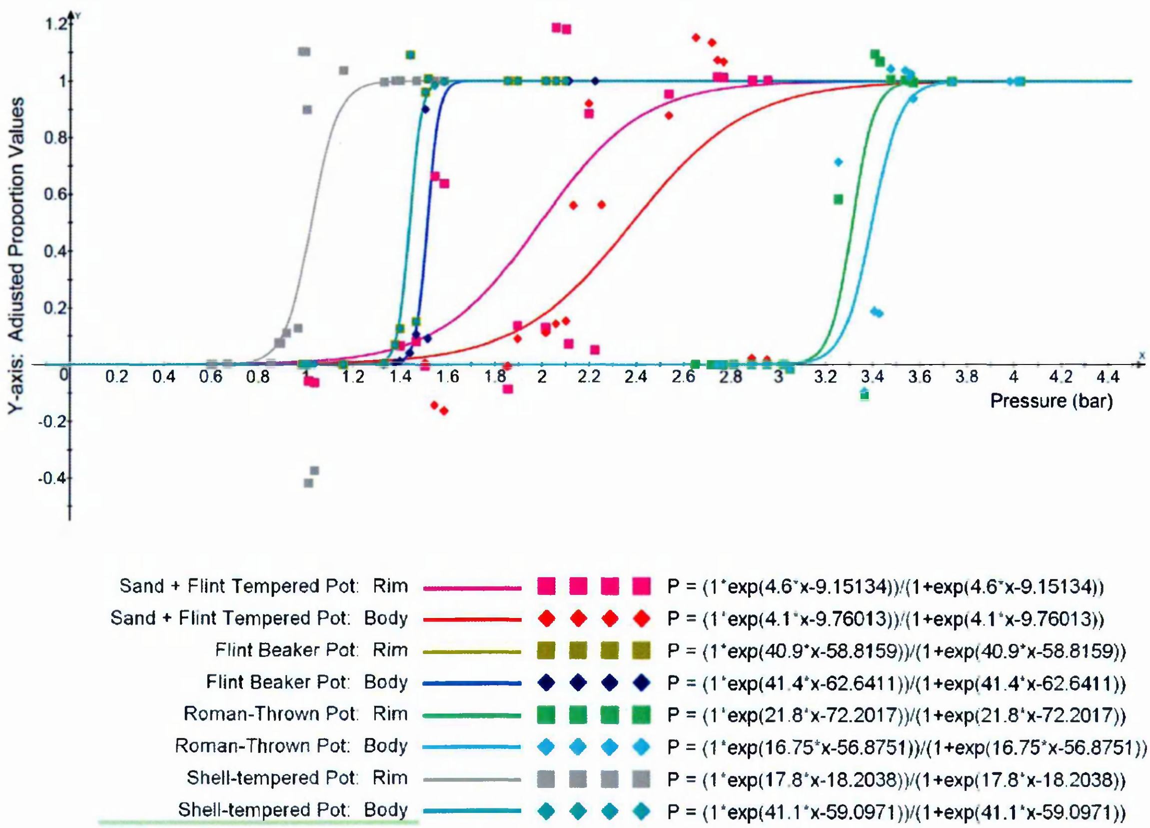


Figure 3.17: The fitted regression model (of binomial proportions; using Logit Link Equation) for the replicate pots.

The data points are adjusted proportionately to reflect an averaging over the Trial factor in the statistical analysis. The value of 1.0 on the Y-axis represents the point where 100% of the pots would be broken at the corresponding pressure on the X-axis. Error cannot be represented (see section 3.4).

Table 3.4: Accumulated deviance analysis for the broken pot dataset.

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx chi pr
+ Pressure	1	17.8587	17.8587	17.86	<.001
+ PotTreatment	7	96.7843	13.8263	13.83	<.001
+ *Pressure.PotTreatment*	*7*	*25.6968*	*3.6710*	3.67	<.001
Residual	132	70.3769	0.5332		
Total	151	210.7167	1.3955		

The regression to of breakage to pressure, to pot treatment (type), and to pressure within each pot type is considered significant.

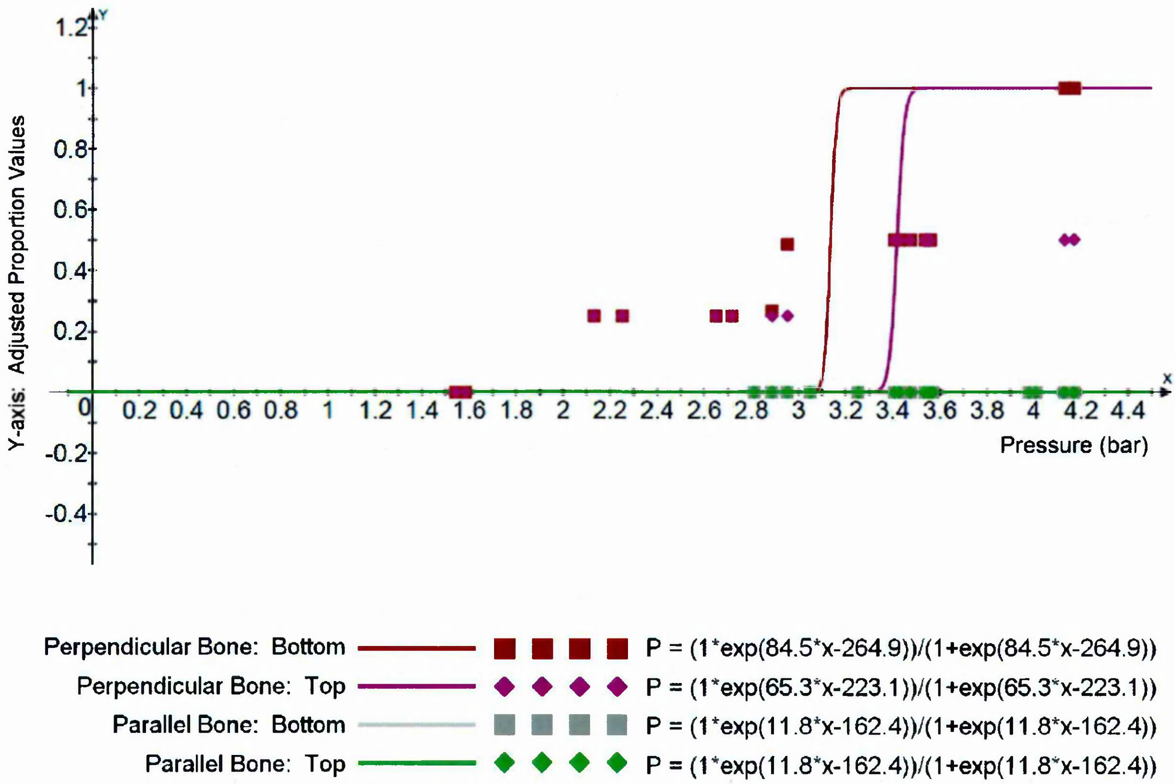


Figure 3.18: The fitted regression model (of binomial proportions; using Logit Link Equation) for the bones.

The data points are adjusted proportionately to reflect an averaging over the Trial factor in the statistical analysis. The value of 1.0 on the Y-axis represents the point of 100% bone breakage at the corresponding subsurface pressure. The data presented here can be misleading and should not be used for threshold values, although it is useful to show this graph. The fitted model cannot accurately reflect the data properly, since it was not possible to detect significant regression between breakage and pressure (Table 3.5). There was too much variability in the bone breakages. The natural log presented here simply represents median breakage subsurface pressures. It probably also reflects differences in the effects between the four trials. The issue is not that the data are flawed, but that they are not sufficient. If the data were sufficient (*i.e.*, more bones used and/or more trials performed), it would be expected that there would be a breakage and pressure correlation.

Table 3.5: Accumulated deviance analysis for the broken bone dataset.

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx chi pr
+ Pressure	1	1.407E-01	1.407E-01	0.14	0.708
+ BoneTreatment	3	4.791E+01	1.597E+01	15.97	<.001
+ *Pressure.BoneTreatment*	*3*	*9.195E-07*	3.065E-07	0.00	1.000
Residual	53	4.403E-07	8.308E-09		
Total	63	5.548E+01	8.806E-01		

Neither the regression of breakage to pressure nor to pressure within bone treatment (orientation) is significant; however, the regression of breakage to bone orientation is significant as was expected.

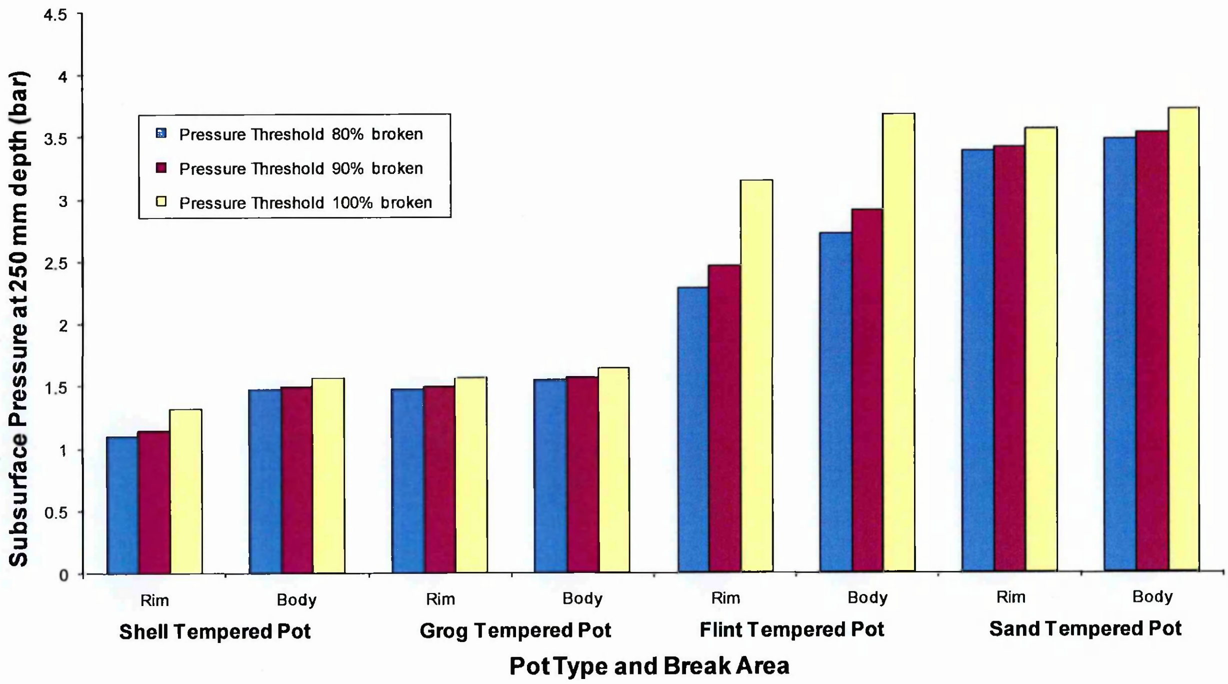


Figure 3.19: Subsurface artefact breakage pressure thresholds for ceramic pots:

Thresholds calculated from prediction equation relative to trial data from replicate pots.

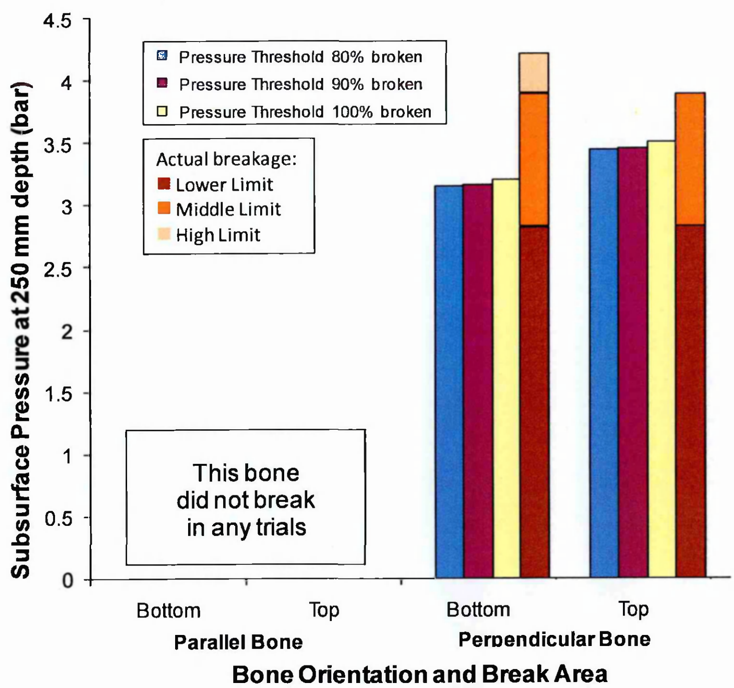


Figure 3.20: Subsurface artefact breakage pressure thresholds for aged bone:

Thresholds calculated from prediction equation relative to trial data from aged bone. Results are from breakage trials using aged non-collagenous human bone. These threshold values may not reflect the right breakage value for buried bones, as the variation within the bone dataset proved too high to support significant regression between breakage and pressure. The graduated orange bars show the actual breakage that occurred within the trials.

3.4 Discussion

The laboratory methods were designed carefully, but adjustments and developments were made to address problems, improve effectiveness, and adjust the experiment to reduce data variability.

3.4.1 Soil preparation

A key factor in the laboratory work was the soil preparation within the soil bin. The purpose of using a soil bin is to have a controlled environment which is not available outdoors. A drawback of using this controlled environment is that the soil is never going to exactly match field soil, as the only factors which determine soil structure are the soil processor and its operator. The processes involved in natural soil structuring and soil health do not exist within an indoor soil bin environment. Nonetheless, by careful monitoring and optimization, it is possible to achieve constant, repeatable soil conditions.

Even so, there were some things, which if avoided, could have reduced the observation of variability (and thus magnitudes of error) in both the soil pressure measurements and artefact breakage. The laboratory trials were conducted at the same time as another trial, using the same soil, but on alternating days/weeks of soil bin use. The other project used a shorter section of the soil bin's length. It is believed that if the soil bin were used exclusively by this study, the pressure and breakage data could have been of a higher quality. This is because, as different areas of the soil are treated differently, variation in the soil density and areas of deep compaction occur. While the soil lane was re-prepared prior to each trial within this study, the full depth of the soil in the soil bin was not removed nor re-moulded. Thus, it is hypothesized that the areas of soil used by both projects became different to those used exclusively for this study.

The purpose of using the soil bin laboratory was to engage a controlled environment where issues affecting data variation could be limited. Without sufficient care in preparing the test medium – the soil itself – the laboratory trials could have been rendered unsuccessful. To provide a quick test for quality assurance purposes and to monitor the overall soil preparation before each trial, a penetrometer was used to test the variation in resistance to penetration along the length of the soil bin. This was done after each soil preparation, before object burial. This penetrometer test provided a check that there were no large variations within the soil profile. It also encouraged the technical staff to attend to detail when preparing the soil for these trials. It is believed that if the soil was not prepared consistently down the length of the soil bin, the induced variation to the subsurface pressure generation and object breakage would be great enough to significantly affect the experiment.

No other technique was used other than the penetrometer to monitor soil variation before experimentation. Further intrusion into the soil profile was unwanted, as this could have negatively impacted the integrity of the soil preparation. Although soil variation could have remained even after evaluating soil variation down the length of the soil bin with a penetrometer, this issue did not seem to have a major effect on the study results. It was possible to analyze the data without encountering any skews or patterns in the data indicating a problem with soil preparation. While this research is not believed to be significantly compromised, if similar laboratory trials were ever conducted or this same research repeated, it would be wise to improve this area of the experiment.

Another issue was the possibility of point-loading on the pressure sensors and the buried artefacts. This was a concern, as small rocks, other debris within the soil, or very hard or dry soil clods within the soil could exert higher forces than those arising from pressure transfer from the bulk soil. Small point loads could have caused stress concentrations, which in turn could have caused premature breakage or puncture failures in the artefacts. If this had occurred on the surface of the buried artefacts specifically in the area of the painted-on conductive trace, breakage could have been falsely and/or prematurely indicated. Likewise, if a small point load was applied on a portion of the small ceramic pressure sensor, the sensor would report a pressure reading much higher than the actual subsurface pressure acting on the buried objects, affecting the quality of the information gained about peak pressures. It is believed that if a soil sieving system was used to remove all small rocks, soil clods, or other debris during the burial process for the soil surrounding the buried objects in the trial, the risk of point loading would be greatly reduced. Although a soil sieving system was not employed during this research, the issues were not ignored. Rocks and other hard debris or soil clods were picked out by hand during object burying. It is believed that most of the larger objects were removed.

3.4.2 Buried artefacts, instrumentation, and breakage detection

The quality of the artefacts affects the integrity of the experiment.

The handmade artefact pots were created within specific standards defined for this research. The potter worked to the specifications, albeit some small changes were necessary in order to achieve pots that would not fall apart while in the kiln. However, it is the differences between pots of the same type which could have been minimized. The results of this study do not suggest that this was a significant problem, but if this study was to be repeated it would be wise to address the issue. It is suggested, in addition to following the specifications set by the archaeologists, that the exact size and wall thicknesses of the pots be better matched with others within the same pot-type group. There were visible differences between pots of the same type within this study, and the results would be less variable if these factors had been better controlled.

Bones are and always will be variable relative to each other. The bones were not manufactured, and so had inherently variable internal structures. The radius bones were selected so as to be as similar as possible. The bones would have had pre-existing differences in bone density, cortical bone thickness, general length and width, and may have had micro-cracks in the bone structure. All of this would have affected their ability to resist breakage during loading. This study was able to measure length and width (Appendix L), but did not have the resources to quantify any of the other areas of variation. An x-ray machine (or some other density and or imaging analysis) might have been able to identify density and micro-cracking, prior to the trial. This would have allowed the existing state of the bones to be assessed. This information could then have been factored into the data analysis. It is recommended that resources should be found to quantify the bone's physical properties better before testing, so that these factors may be considered relative to the results.

Both the pots and bones were instrumented in the same manner, using a painted-on conductive trace that broke with the object causing a change in electrical resistance. The instrumentation worked well, and the conductive trace system and its implementation allowed detection of breakage. One aspect of this system that helped its success was an appreciation of the importance of establishing a good quality water-resistant layer to seal off the conductive circuit trace from corrosion due to moisture in the air and soil. For this reason, a special water-resistant lacquer was used and the pots were sprayed with their final coat of lacquer the day before the trial to ensure freshness of the lacquer and viability of the procedure. If this had not been done, the moisture in the soil would have quickly degraded the conductive trace and the breakage of buried pots and bones would have been impossible to detect.

The interpretation of breakage events from the recorded circuit traces was a key task. The breakage detection system did a good job at showing when the pot cracked and finally broke. To avoid any bias, an automatic decision-making method was used to objectively evaluate the breakage. Unfortunately, variation within the trace recordings was too great and the final decision to classify a buried object as broken or not broken had to be made by the author of this research. While an automated decision making system was attempted without success, it could provide a model or basis for a purely objective and reliable breakage designation system in further studies.

3.4.3 Subsurface pressures

A methodology developed during experiments in the laboratory greatly improved the outcome of the final trials. This involved a switch from the use of multiple tyres to one single smooth tyre. The benefits of using only one tyre had not been anticipated at the outset of the project. After the pilot tests, where a large range of tyres was used, it was obvious that the original system was too cumbersome, time and energy consuming. There was also the added safety risk from the extra kit necessary to change tyres, handle the weights, and manage the various tyre rigs.

Using the single smooth tyre, the mean peak subsurface pressures generated from all five trials in this study ranged from around 0.7 bar to around 3.7 bar, over 6 different tyre passes (runs). The resolution of the successively higher magnitudes of pressure was about 0.65 bar. In previous trials, either a range of multiple tyres or a single treaded tyre was used, and the heterogeneity of subsurface pressure generation and opportunity for mistakes was high. This study achieved a substantial improvement over the previous methodology. Using a single smooth tyre, without any necessary changes to the macro-setup of the experiment once each trial was started, allowed a more reliable and controlled experiment.

3.4.4 Breakage results

The breakage evaluation was done by relating the run in which the pots and bones broke (via instrumentation), to the peak pressures recorded by the pressure sensors within that run.

The experiment produced discrete results. This was unavoidable because of experimental constraints. The treatment of the soil was of paramount importance. The pots, bones, and sensors were hand-buried (due to the fragility of the buried objects and the necessity to treat them similarly to the sensors), an operation which was time-intensive. Once buried, the ceramics and bones could not be dug up until the end of each trial. An excavation operation would have disrupted the soil above and around the objects, altering the breakage dynamics.

The inability to gradually and continually increase pressure on a buried object is inherent to the *dynamic* surface loading of the soil. The tyre must continue rolling over the object (at the controlled laboratory speed), and if it stops the strain-rate loading properties of the soil will change the pressure transfer dynamics operating under the tyre and around the buried object.

The only way to 'simulate' a continuous test would be to do many more tyre passes, with smaller progressions in load and pressure magnitude. The difference between subsurface pressures generated under the chosen case load-pressure cases would only need to be more than the sensor variation so that the peak pressure outputs between runs would be significantly different from each other (to correlate to consequent breakages). The variation of the sensor outputs in this test was between 0.2 and 0.3 bar (the mean difference between the peak subsurface pressures between runs was 0.65 bar). This is not high, but it would be best to attempt to lower this variation. To lower the variation of the sensor outputs, more sensors would need to be used, and the quality and consistency of the soil preparation would have to be carefully monitored and approved before each test. Altering the methodology as above would allow a close simulation of a continuous-type test. This could also however, have a negative impact on the soil, as each tyre pass causes some soil compaction (the magnitude of the increase of compaction depends on the loading). Also, sustained multiple tyre passes could cause the soil to behave differently, and some type of pre-compacted pan might form on the upper layers of the soil, affecting the pressure transfer to the pressure sensors. The next tyre pass would then affect pre-compacted soil, and the pressure transfer dynamics would change. Creating a more continuous trial methodology based the above suggestions therefore has a trade-off, and the decision on how to design the study would depend on the research aims.

Only six (6) tyre passes (runs) were performed in this study. This was considered acceptable, both in the minimization of the multiple passes effect on the soil and the resolution of subsurface pressure generation. The subsurface pressures generated within each run through all trials were significantly different from each other under each load case, and it was possible to identify differences in the breaking points between the pot types. The soil was also relatively unaffected so the results should not have been greatly biased by pre-compaction of soil due to repeated tyre passes.

The threshold results also allowed the pots and bones to be compared to each other relative to their individual abilities to resist subsurface breakage. It was anticipated that the pot materials would have different strengths; however, the extent of these differences was unknown. The results show the fragility and strength of each pot type in relation to each other. It would be interesting to follow this study up with a test of the material strength of each pot type's ceramic material to verify the 'weakness' and 'strength' that has been observed in this study.

The material strength properties of the bones were unknown. Literature on aged non-collagenous bone strengths is sparse, and reliable numbers could not be found. As there were no x-rays taken of the bones prior to the trials, the internal structure and density of each bone could not be evaluated and identified. The possibility that there were internal micro-cracks or other defects in or damage to the bone structure was not investigated. The bones were evaluated by visual observation, which was considered suitable based on initial results obtained during setup of experimental design prior to the breakage trials. This technique was robust enough to enable bones of a similar quality, size and type to be chosen. Simon Mays, the English Heritage Human Skeletal Biologist, also confirmed that the bones were of similar age and status – from adults similar in age (living sometime in the medieval period) and without obvious bone disease present that might affect the breakage dynamic.

Since all the bones were non-collagenous, their breakage dynamic was similar to that of the replicate ceramic pots: *I.e.*, they were brittle. Thus, it was not possible to predict at what point the bones would break, but it was known that if they broke, they would break cleanly with minimal bending. These estimations were correct, as the bones that were orientated perpendicular to the tyre path did break cleanly in the middle. The parallel bones never broke, and thus the only conclusions that can be drawn are that a) the pressures were never high enough to break a human radius bone in that orientation, and b) that a crushing failure of the radius bone was also resisted successfully.

It was observed that the pot rims always broke before or at the same time as the pot bodies. The shape and rim diameter relative to the pot body diameter did not seem to affect this order of breakage. Most of the pots had a rim a little wider or the same size as the pot body, explaining why the rim broke first. The quartz tempered pot was different, as its rim was not as wide as its body and so it might have been expected that the body would break before the rim, but this did not occur. This indicates that for pots buried on their side, the rim will usually fail first – suggesting that the breakage propagates from the rim into the pot. More research could be done on this aspect of breakage dynamics.

The critical result from the pot breakage data in the study was the lowest breakage point of 1.3 bar. This provides a reference point to pot breakage indicating the 'worst case scenario' for the most fragile pots. The other pots broke at higher subsurface pressures, ranging thus from 1.3 bar to 3.6 bar.

The breakage dynamics of the bones showed that the perpendicularly orientated bones broke primarily in tension. This was confirmed in one trial where the bone only partially broke – the bottom cracked, but this crack did not travel through the entire diameter of the bone and thus the top trace was never broken.

It should be noted that the orientation of the bones was a very important factor. The parallel orientated bones never broke in this study, while the perpendicularly orientated bones generally did. The amount of variation between bones has been discussed, but it is proposed that variation between bone structure, density, and quality is the cause of the large variation in breaking points of the perpendicularly orientated bones.

The radius bones were chosen for use in this study for the reasons presented in the methods section (see Section 3.2). It would be interesting to perform a similar study on other bone types, to see the effect that bone type has on the breakage threshold. Inferences can be made as to how other types and sizes of bones would break under dynamic surface loading. A femur bone would probably break in a similar fashion to the radius bone - cleanly in the middle if orientated perpendicularly to a tyre path and perhaps not at all if parallel to a tyre; however, the subsurface pressure at which it might break could be different. This would depend on tyre and load type, also on the pressure propagation dynamics of the tyre relative to the bone size. The femur is a very long bone, and as its length would span a larger portion of the tyres footprint, the force to resistance ratio would change, so the bone could theoretically break at a similar threshold to the radius bone. More study is needed in this area.

A definitive result cannot be taken from the bone study. Nonetheless, the lowest peak subsurface pressure at which the bone broke could be taken as an indication of a 'worst case scenario'. While not prescriptive for land management practices, it could be recommended to avoid pressures over 2.8 bar (the lower limit of bone breakage in this study).

Both the pots and bones are made of brittle material, and thus break cleanly at a specific loading. The subsurface pressure thresholds presented in the results showing 80%, 90%, and 100% breakage are useful indications of how limitations placed on field operations could prevent buried artefact breakage. An archaeologist or land manager interested in preserving or minimizing damage to buried artefacts might choose to limit subsurface pressure generation to correspond with one of the percentage thresholds. This would have a direct impact on the specifications of the vehicles planned for use in field operations.

3.5 Conclusions

The factors involved in this study were numerous. The experimental methodology contained novel techniques, such as the instrumentation to detect pot and bone fracture, and the system developed to generate the incremental range of subsurface pressures. The experimental methodology should be considered a success, as there were no major issues with the final trials that prohibited data collection and result analysis.

The use of the smooth tyre allowed pressure generation with no anticipated stress concentrations in the soil. The subsurface pressures generated were of the correct magnitude and resolution to detect breakage of different types of buried objects at different pressures.

The instrumentation methods gave consistent and reliable results, and allowed breakage to be detected while objects remained buried.

The data analysis allowed correlation between peak subsurface pressures and object breakages. The prediction model can be used with data external to this breakage study to gain insight into buried artefact breakage under real-life field vehicles and operations.

The results from the pot breakages show that different types of pots have different material strengths and thus different breakage dynamics. The results show the strengths of these pots in relation to each other; however, with the prediction model, they can be compared with other data if future studies are done on buried artefacts. It can also be concluded that the rims break before or at the same time as the body of the pots, as in this study the body never broke before the rim.

Relating to the breakage points of each pot type, we can conclude that:

The shell tempered pot is the weakest, failing at 1.3 bar
The grog tempered pot is second-weakest, failing at 1.6 bar
The flint tempered pot is the third-weakest, failing at 3.1 bar
The sand tempered pot is the strongest, failing at 3.6 bar

The results also show that orientation has a large effect on the breakage dynamic of buried aged non-collagenous human bone. Within this study, the parallel orientated bones never broke, while the perpendicular bones broke most of the time. The perpendicular bones always broke cleanly at or near the middle of the bone, and the parallel bones did not exhibit any signs of crushing failure. We can thus conclude that the radius bones orientated parallel to the tyre path did not experience any pressure high enough to cause damage (whether in a clean transverse break or by crushing), and that the perpendicular bones were in danger within the subsurface pressure ranges that we used in this study. If any other studies of buried bone breakage are conducted in the future, the variation of bone structure, density, and quality between bones should be carefully documented and considered in the data analysis.

The variation of material naturally present in the radius bones meant that a significant regression was not possible from this study. However, an indication of bone breakage threshold can be seen, as the weakest bone in the perpendicular orientation broke at 2.8 bar.

The prediction model constructed in this study can be used to predict the possibility of artefact breakage. The charts indicating the 80%, 90% and 100% total breakage can also be used as a guide for buried artefact damage prevention or mitigation.

When applying this information in other situations, it should be remembered that local soil conditions must always be taken into consideration, as changes in vehicle specification (thus loading magnitude) and soil status have a large effect on pressure transfer, and thus are important to consider when estimating buried artefact damage.

Chapter 4: Subsurface Pressures from Field Operations

4.1 Introduction

This chapter focuses on the magnitudes and mechanisms of subsurface pressure generation through soil from dynamic surface loading caused by a variety of conventional agricultural field operations. Within this fieldwork portion of the research, the effect of different cultivation regimes {inversion, shallow inversion, non-inversion, zero till} within an otherwise conventional annual field operation sequence (cultivation, drilling, rolling, spraying twice, harvesting and loading vehicles with harvest for removal) was analyzed relative to magnitudes of generated subsurface pressures. The dynamic surface loading from each field operation was also evaluated relative to resulting peak subsurface pressures. Finally, the variation of the soil moisture content between periods of cultivation sets was evaluated for any positive or negative effect on peak subsurface pressures.

The utilization of a field environment allows experimental investigation of subsurface pressure generation within a less-controlled genuine farming context. The field site chosen for this work has a sandy loam soil, which is very similar in texture to the soil bin soil used for the laboratory breakage trials. In addition, the agricultural operations involved within this field study are used in many if not most cultivated fields in England. Each vehicle, tillage tools, and relative specifications were chosen so that they would be reflective of the contemporary *status quo* within the farming and land management community. Soil work was performed seasonally, and all operation of farm machinery and soil work was performed by an experienced operator.

The data output from this study yields a comprehensive record of peak subsurface pressures under conventional field operations. This valuable information provides a point of reference for those interested in subsurface pressure generation under field operations. Within the context of this research however, it was designed to interpret the breakage thresholds established in the previous chapter. In this way, field operations that either protect or threaten buried artefacts can be identified, and best-practice suggestions for field management involving buried artefacts can be proposed.

4.2 Methods

The fieldwork component of this study consisted of investigations into the magnitude and variability of pressure transfer under the wheels and tracks of field vehicles between four different cultivation treatments.

The wheels and tracks were seen to be the main propagators of subsurface pressure from field operations (see Appendix F). When comparing subsurface pressures under wheels and tracks to those of tillage tools and implements, the magnitudes of subsurface pressures generated by implements and tillage tools were found to be of two orders of magnitude less than that of wheels and tracks. The largest pressures resulting from the furrow press (0.30 bar), heavy roller (0.27 bar), and DD Rolls[1] (0.11 bar), while all other tillage implements generated subsurface pressures of less than 0.10 bar.

A field site on the Cranfield University farm accommodated four experimental plots. The site was setup in summer of 2005, and was left to rest and regain its integrity over the winter. The field had previously been cultivated with wheat and ryegrass.

The experimental field site was chosen with location and soil type in mind[2]. Important considerations were access, proximity to main buildings, and technical support. The soil was a freely draining sandy loam, identified as a Luvisol within the World Reference Base classification (FAO, 1998), with some areas transitional into the Cambisol group, where there is less clay accumulation in the lower horizons. The choice of a sandy loam soil enabled field machinery to travel over and work the land over a wide range of soil moisture content.

The weather affected the management of the field operations. Another factor was the availability of machinery. The operations in this study were carried out largely with agricultural equipment on free loan, sought out and appropriated each time field operations were performed. Obtaining, assembling, and using such a large amount of equipment over a long period of time was a challenge.

The soil moisture content was variable throughout the field trials. The sandy loam soil did help to keep soil conditions similar during periods of fieldwork as the lower clay content reduced the amount of water retained after small precipitation events and thus the impact that change in soil moisture might have had on the overall soil status and workability. The natural heterogeneity of the soil on site, and daily differences in soil moisture, soil and air temperatures, levels of precipitation, humidity and wind speed all contributed to variability in the soil between periods of fieldwork.

Acknowledging the variability of soil status between and during fieldwork was essential as it was not known to what extent it might affect the results. Moisture content was thus a particular variable considered in the data analysis to assess its effects.

Limited ability (inherent in using loaned machinery) to retain the same models/makes of vehicles and equipment for consecutive fieldwork periods imposed slight differences between exact

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[1] A set of hollow formed pressings strung along a horizontal bar the width of the implement gang, where each DD ring is made up of two pieces of thick sheet iron pressed so that a cut-away section resembles that of a two uppercase D's facing each other in profile. This operation is used to pack soil behind an implement, and will also break bigger clods of soil with the sharp edge at the ring center where the two D-shaped rings meet.

[2] The field site, being relatively easy to work, would have been attractive to past historic and prehistoric peoples as habitable or arable land. Indeed, during this research, several Anglo-Saxon and Bronze Age artefacts were found on-site. This aspect of the site is important given the role of archaeology within this study. It indicates that this site was similar and thus can be representative of other areas in England that contain valuable artefacts. This connection allows the findings from this research to be applied to other sites and situations across England.

vehicle specifications of some of the operations from one fieldwork period to the next. However, the size, weight, tyre pressures, and character of each operation were kept as consistent as possible. Different tractors and tillage implements were employed, but their specifications were similar enough to ensure that the results were not unduly affected.

The four field plots measured 10 m by 20 m and were side by side in the same field to keep field conditions as consistent as possible. Each plot was submitted to one of four different cultivation schemes: inversion, shallow inversion, non-inversion, and zero-till. In each plot, three pressure sensors (the same as used in the soil bin laboratory, Chapter 3) were installed at a depth of 250 mm, with the ceramic strain-gauge pressure sensors located at the 0°-360° position (the top) of the aluminium cylinders in which they were mounted. In a previous study (Chalvantzis, 2005) this orientation was shown to experience the highest subsurface pressure under dynamic loading relative to the seven other cardinal and intercardinal points that were tested. These were buried in-line with each other, so that vehicles would drive directly over them in a straight line when positioned correctly. See Figure 4.1 for field layout.

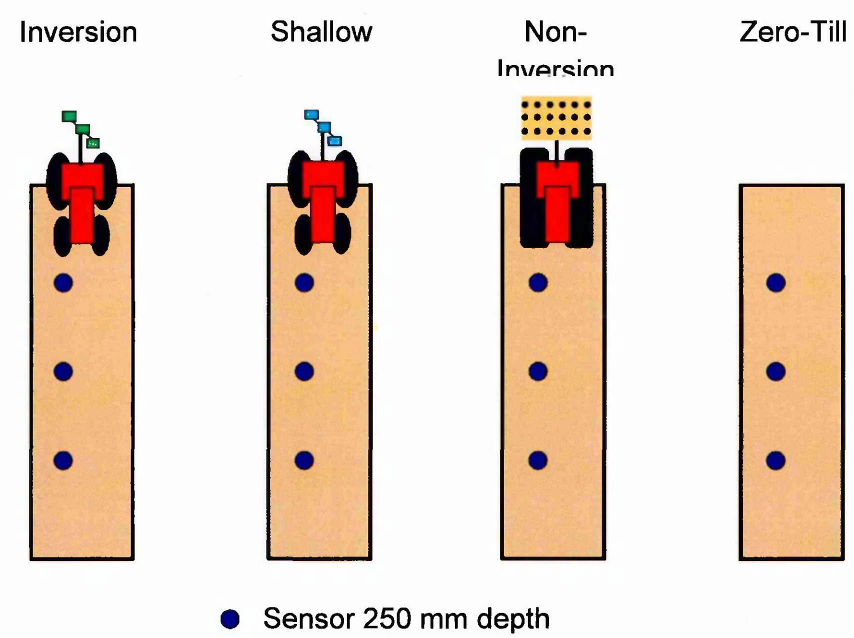

Figure 4.1: Field plot layout showing sensor locations and plot treatments, with no cultivation in the 'Zero till' plot.

Each plot was subjected to the equivalent of a year of field operations. These were, in order: cultivation, drilling, rolling, spraying (twice), harvesting and loading of the crop. This was done in an accelerated time frame, and thus, five (5) year's of field operations (performed sequentially) were performed over a period of about a week (depending on weather and machinery availability).

For each plot, the designated cultivation type was performed within the cultivation operation; otherwise, all other field operations were the same for all four plots. The first field plot was subjected to conventional inversion tillage, ploughing. The second was assigned shallow inversion, or shallow ploughing. The third was subjected to a non-inversion form of cultivation, done with a "Simba Solo" implement set. The fourth plot was left without any form of tillage, thus 'Zero-till.'

After the cultivations, the plots were all subjected to drilling (seed-drilling, but no seeds were used), rolling with Cambridge rolls, spraying (assuming the farmer sprays twice per crop cycle, so two passes of the sprayer), a harvester-type operation, followed by a tractor and trailer.

These field-going vehicles all passed over the same wheel tracks, to try and ensure that every wheel, track, and farm implement passed over the buried pressure sensors. The same type of pressure sensors were used, recorded in the same way as outlined in Chapter 3 (FYLDE data processor and acquisition, DasyLab 8.0 software). Figure 4.2 presents a sample pressure trace for each plot's cultivation operation.

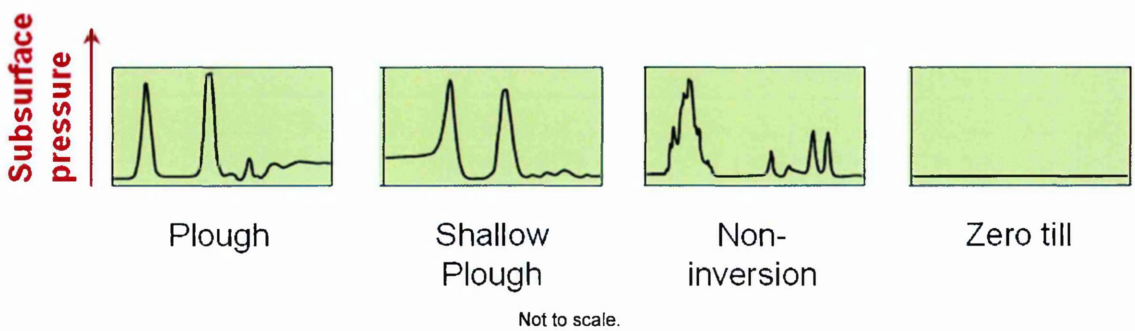

Figure 4.2: Sample pressure traces

The expected output format from the pressure sensors for cultivations within the sequence of field operations for each field plot.

The field moisture contents are noted in Table 4.1. For each cultivation period, the moisture content was tested for with a volumetric moisture sensor, the Delta-T ThetaProbe Soil Moisture Sensor (ML2x). Since cultivation sets lasted anywhere from a few days to a week or more (depending on weather and machinery status), there was a range of soil moistures collected for each period. The median of the soil moisture range for each cultivation period was chosen as the soil moisture indicator value, so that the soil moisture status could be analyzed for effect on soil pressure transfer (in order for a co-variant to be considered it had to be a specific value).

Separate sets of five-year field operation 'cultivation sets,' were conducted, and were repeated, with at least a month between the five-year sets of field operations. The repetitions covered a total of 30 years of accelerated operations. Table 4.2 presents basic specifications of the farm implements, tillage depths, tractor types, vehicle weights, and tyre pressures used during field operations.

Table 4.1: Cultivation sets, dates, and moisture content measurements for all plots in the accelerated field trials.

Cultivation Set	Date	Moisture Content Range	Median of Moisture Content Range
YEARS 1-5	September 12 – 13, 2006	10-15%	12.5
YEARS 5-8	October 16 – 18, 2006	22-30%	26.0
YEARS 8-15	May 21 – 24, 2007	15-24%	19.5
YEARS 15-20	October 4 – 8, 2007	9-18%	13.5
YEARS 20-25	April 21 – 22, 2008	16-29%	22.5
YEARS 25-30	May 14 – 20, 2008	13-26%	19.5

See Appendix G for full spreadsheet of specifications

Table 4.2: Basic Field Operations performed throughout the accelerated field trials.

Field Operation	Depth (mm)	General Vehicle / Implement Type	Approximate Weight (tonnes)	Front Tyre
Cultivation Plot 1 Plough	250	Mid-size Tractor 4wd	5.5	All tyres and inflation pressures typical and normal to tractor or vehicle (one exception for the Rolling operation with tractor using Low Ground Pressure tyres)
		4-share reversible plough	1.0	
Cultivation Plot 2 Shallow Plough	125	Small tractor 2wd	2.0	
		2-share non-reversible plough	0.2	
Cultivation Plot 3 Simba Solo	125	Large tractor 4wd	8.0	
		Combination tillage set	7.0	
Cultivation Plot 4 Zero Till	0	(Nothing)	-	
All Plots Direct Drill	75	Large tractor 4wd	8.0	
		Midsize drilling system with discs	3.5	
All Plots Roll		Midsize tractor 2wd	3.5	
		Cambridge Rolls*	3.0	
All Plots Spray 1		Spraying vehicle with full tank water	6.0	
All Plots Spray 2		Spraying vehicle with full tank water	6.0	
All Plots Harvester		Harvester**	15.0 – 23.0	
All Plots Tractor-Trailer Combo		Large tractor 4wd	4.5	
		10 t capacity monocoque trailer	3.5	
		Trailer with load	8.5	

* The Cambridge roller is a land roller constructed of ribbed iron rings threaded onto a central axle. The rolls used in this study weighed approximately 3 tonnes and had three separate sections of axle-mounted iron rings.

** For some cultivation sets, due to limited machinery availability, a heavy tracked tractor (15 t) was used a 'pseudo harvester', instead of a full-size combine. This sufficiently simulated the front end of a combine that normally carries a large part of a combine's load, and thus the results can be compared with either a small tracked combine or to the front end of a normal sized combine if impact of the missing rear wheel is not forgotten. However, a full-size tracked combine was used whenever possible.

See Appendix G for full spreadsheet of specifications

Specific tractors and implements changed over the course of the study; however, the character and basic specifications of the vehicle and operation were kept constant.

4.3 Results

The raw data collected in the field was stored in ASCII text files. One file was generated for every pass of a field operation in one of any four plots. Within that file were the sensor outputs of the three pressure sensors within the plot. The sensor readings were in millivolts (pre-calibration). Thus, the first step in data post-processing was to transform the sensor readings into calibrated pressure (bar).

All field pressure sensors had been calibrated prior to burial in the field, and calibration coefficients had been recorded. This was done with an air calibration system (for details, see Dain-Owens, 2006; for calibration coefficients, as well as the pressure gauge calibration to true atmospheric pressure, see Appendix D).

With the calibration coefficient, the sensor outputs were transformed mathematically into pressure (bar) readings. In some of the files a frequency filter was used to remove frequency noise within the file from the laptop power supply that was used in the field. The noise did not exist in all files, as battery power was used whenever possible. The filter process had no effect on the actual pressure data, as it removed data points that never existed but were just added by frequency interference.

Once the data pre-processing was completed, the values for peak subsurface pressure for the three pressure sensors in each plot within each pass of each field operation were calculated. A small number of data files did not have any data (as a result of the sensors not being run over exactly or in a few instances, not at all): they were removed from the dataset.

Next, the means for the peak pressure values were calculated for all data within all cultivation sets. Originally the number of passes for each operation within each cultivation set was supposed to be five (done in-sequence with other operations; equivalent to five 'accelerated years'), but this was not always the case due to weather and soil conditions. For example, in October 2006 the soil was very wet, so only three 'accelerated' years were completed before soil conditions deteriorated and operations had to be halted until the next spring. There were also some years where data was missing due to malfunctioning of the pressure sensing and data collection system.

Within the peak subsurface pressure calculations, there was one subgroup of field operations that required more data manipulation. The sensor recordings from the inversion and shallow inversion operations within their respective plots necessitated an extra procedure to extract final peak subsurface pressure values. The nature of the ploughing exercise required that the tractor begin ploughing on one of the two edges of the plot, working its way across the plot to fully plough the entire area. As a consequence, it was not possible to line up the wheels with the wheelings (under which the sensors were buried). This meant that sometimes the tractor wheels only ran over the sensors partially.

To retain as much data as possible, multiple files were recorded for all vehicle passes which ran in the near vicinity of the sensors during both the ploughing and shallow ploughing. This resulted in multiple peak pressure values for the inversion and shallow inversion cultivations, and values that were not always similar. Since the study was interested in the peak pressure recorded under every field operation, a method to select one peak pressures from the multiples of peak values was needed.

The following method was devised to select a value that would best represent the peak value but also take into account some of the anticipated error inherently present in the subsurface pressure readings.

It was decided to use the 90th percentile (P90) of each group of multiple values within the inversion and shallow inversion cultivation operations. The identification of the P90 was done in Statistica (version 9.0 by StatSoft Ltd; www.statsoft.com). The values were grouped by operation and cultivation set for the analysis. Two outliers were removed; these were a long way from all the other peak pressure values and would have skewed the analysis (inversion plot, 'year' 6 and 26). Once the P90 values were identified, they were inserted into the main dataset and treated as the peak subsurface pressures for the cultivations for the inversion and the shallow inversion plot.

Finally, the data were organized relative to field operation and field plot. The soil moisture content data was retained within the dataset in order to investigate whether the soil moisture content was affecting the pressure transfer magnitudes between cultivation sets. It was decided to use the median of the moisture content range as a covariate within the data analysis. This would allow the final analysis to calculate whether there was a significant difference between cultivation sets relative to the differences between the respective soil moisture measurements.

It should be noted that no values were inserted into the dataset for the zero till operation. This was done because an Analysis of Variance (ANOVA) assumes that there is a variance within each treatment group, and that for each group, this variance is the same as for the other groups. If zeros were inserted and used as the zero till cultivation values, there would be no variance (no machine ever drove across the plot to cultivate, and thus, every value would be zero) and the results would be biased.

The pressure values were analyzed using ANOVA (in GenStat) to investigate the effect of field operation type, cultivation regime, and soil moisture content.

The structure of the analysis used in GenStat consisted of the treatment as "plot + operation", and the covariate as "moisture_median."

Table 4.3 presents the ANOVA output table summarizing the analysis and presenting the significance of variation between moisture, cultivation scheme, and field operation type

Figures 4.3 and 4.4 show the predicted means and their respective standard error (SE) values relative to the maximum least significant difference (LSD). Figure 4.3 presents the predicted means per cultivation scheme, and Figure 4.4 shows the predicted means for each operation type.

Table 4.3: Accumulated analysis of variance chart for all field data.

Accumulated analysis of variance					
Change	d.f.	s.s.	m.s.	v.r.	F pr.
+ moisture_median	1	0.0033	0.0033	0.02	0.886
+ plot	3	4.4658	1.4886	9.24	<.001
+ operation	10	50.3004	5.03	31.23	<.001
Residual	673	108.4134	0.1611		
Total	687	163.1828	0.2375		

This analysis shows the significance of variation between moisture, cultivation scheme, and field operation type.

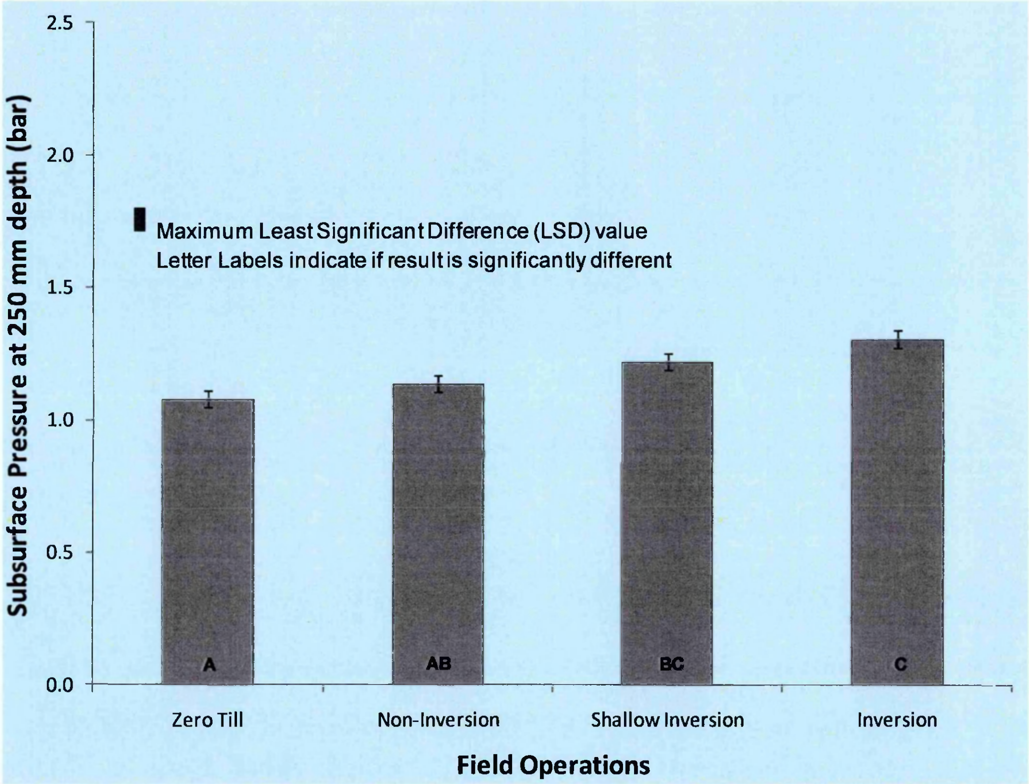

Figure 4.3: Predicted means of peak subsurface pressures for field plots.

Showing the overall mean and standard error of the peak subsurface pressure for each field plot, (maximum LSD value included) from all field operations over all cultivation periods.

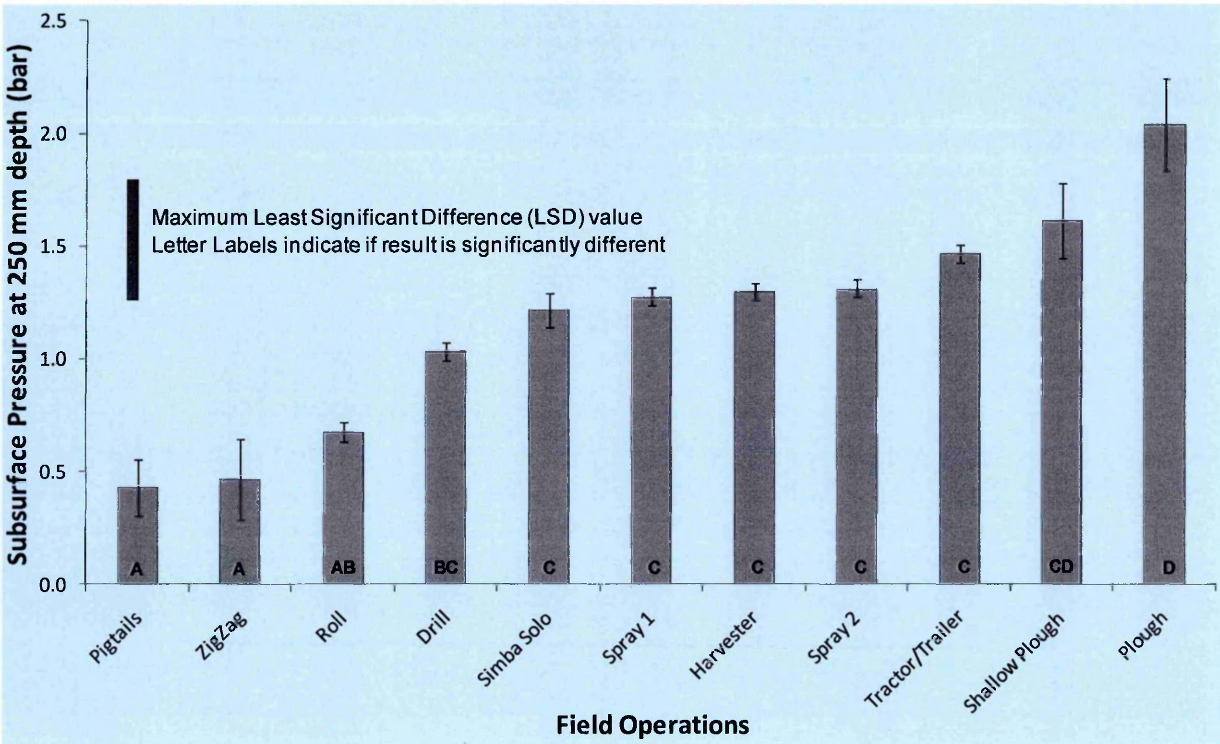

Figure 4.4: Predicted means of peak subsurface pressures for field operations.

Showing the overall mean and standard error of the peak subsurface pressure for each field operation, (maximum LSD value included) from all field plots over all cultivation periods.

4.4 Discussion

4.4.1 Experimental Design

The fieldwork required much planning and pre-installation of sensors and associated equipment.

The method of sensor burial was different from that in the laboratory. The top layers of soil were temporarily removed while buried objects were positioned. The top soil was reinstated after all instrumentation and objects were in place, and then the field plots were left to rest over the winter (as would be done with a cultivated and crop-sown field in normal winter conditions). This resting period was required to allow the disturbed soil to reform so that the pressure transfer under the field operations could be more representative of normal field conditions.

The sensors were buried carefully in an exact location, measured out manually in the field. Surveying was used to locate posts within the field from which measurements could be taken to relocate sensor positions. This was considered an adequate and accurate method for sensor location. However, once the trials started, issues arose relating to the sensor location method. The manual method of re-measuring to find the sensors each time the field plot was cultivated or submitted to any field operation was time-consuming; thus, it is thought that sometimes this re-measurement process may have been shortened or omitted. Certainly, there were some inaccurate determinations of sensor locations, and accurate tractor wheel passage over the pressure sensors was particularly difficult for the plough operation. Due to the nature of this operation, the ploughing of the plot sometimes began on the other half to where the buried pressure sensors were located. In order to even semi-accurately assess whether or not the tractor's wheels would eventually pass directly over the buried pressure sensor required much measuring and exact lining-up of the tractor wheel base and the sensors, which was not feasible due to time constraints. Since the fieldwork trials were conducted over an extended time period, enough good data was collected to compensate for any missing, inconsistent, or misleading data, and the integrity of the study was not compromised. However, future studies should anticipate this issue, especially if the study is smaller in scale, as lack of data could impede assembly of a complete dataset.

In a laboratory setting, it is relatively easy to control exact locations of materials and implements involved in the experiment. In the field, this becomes much harder. One means to solve this issue could be to survey the pressure sensor locations using GPS. The sensors' locations could then be physically relocated every season fieldwork recommenced. Also, the sensor location could be programmed into a vehicle's positioning-control system (GPS or RTK positioning systems) to ensure that the wheels and/or tracks would pass directly over the small ceramic sensors. This should increase data quality and reduce the amount of lost data, being especially advantageous in field experiments with less data collection.

Another important aspect of the fieldwork is the attention to constantly checking and re-checking of the wires, contact points, and general working order of the electrical wiring and sensor cables. Open wires, plugs, solder points, and other types of electrical wiring were waterproofed as much as possible. A field box housed the endpoints of the sensor cables and data-logging connections, and much attention was given to ensuring that the wires and plugs connected to the buried pressure sensors remained out of sitting water. Ambient humidity and general wetness was expected, and it was important to monitor the field wires before every field session to check for malfunctions due to exposure to moisture and other causes, including rodent damage. The resistance values for the strain gauge pressure sensors were also checked to confirm that the pressure sensors were working properly before every field session.

Other issues were also considered that might affect the outcomes of the field trials. One uncontrollable factor thanks to the outdoor setting was the moisture content of the field soil. The moisture content variability can be analyzed both spatially and temporally.

Variability of the soil moisture between and within plots was inherent to the soil and the micro-topography of the field. It could also have been affected by differences between cultivation and tillage techniques.

Generally, spatial variation is overcome within experimental projects by creating an experimental design that includes random and replicated plot placement within the field (or fields). In this case, this was impossible. Having a large random plot design would have exceeded the scope and resource-base of the research, as the space and machinery requirements would have become prohibitive. However, it is expected that any differences in moisture content generated by plot placement would be minimal; indeed, the soil textural analysis done of the field soil from each plot did not show significant differences between the plots. Variations in moisture content due to cultivation regime were unavoidable.

A practical approach was taken with regard to the temporal variation of moisture content over longer-term time periods. The moisture content was measured and recorded over all plots (individual plots were not tested). The median value of each range of moisture content per cultivation period were incorporated into the statistical analysis as a co-variate, and thus this information was quantified and evaluated relative to pressure transfer magnitudes.

4.4.2 Soil Management

Soil management was also an important part of the field experiment. The experiment was intended to mimic real arable production practices; however, there were some differences between reality and the experimental field environment.

No crops were grown throughout the field experiment. Weeds were allowed to grow, and thus smaller amounts of above and below-ground biomass did become incorporated into the field experiment. The weeds were sprayed off before each set of field operations mainly for overall control of adjacent field weed populations. The decision to not crop the field during the experiment was made to reduce and potentially eliminate variability arising from crop residues and root structure.

The possible effects that a cropping system would have had on the experiment are worth discussing.

The above ground biomass present from a crop would have been more than that from the weed growth within the study. After harvest, depending on the crop type residues would have been incorporated into the soil profile (or not) according to the cultivation regime assigned to the plot. The inversion cultivation techniques would have mixed the organic and un-decomposed material into the soil to the depth of ploughing. The non-inversion cultivation (this experiment used a Simba Solo) would have broken down the root structure at the surface of the soil, mixing it and other crop residues in the top layer of soil, not necessarily burying it. The zero till cultivation plot would have left the crop residues on the soil surface, and although the subsequent drilling operation would have dispersed some of the surface roots from the previous season, organic material would have remained *in situ*, decomposing naturally as the new crop grew through it.

These differences in the fate of crop residues between cultivation techniques would have affected the amount of organic material in the soil, and could also have dictated a different system of pest and weed control. There may also have been a long term effect on the requirement of fertilizer additives throughout the growing season, as the tillage techniques also dictate the amount of organic material left in the soil, the self structuring ability of the soil, and the chemistry of the nitrogen cycle.

The below ground biomass would have differed for other reasons, as well as extent of crop residue incorporation. As roots grow, they physically bind together larger peds and aid aggregate formation by binding particles with the mucilaginous layer on the outside of the plant root. Different types of crops have different root structures and rooting depths, as well as overall root mass. For example, the roots from maize will grow to a depth of around 2.4 m and are compromised of a robust, dense, and articulated root system with a lateral spread of 1 m on all sides (Weaver, 1926b). Barley has finer, less dense root growth, with the lateral roots remaining within the top foot of soils and a few deep roots reaching a depth of 1.5 m or more depending on the soil (Weaver, 1926a). The root system of a pea is different, with a fine but dense root system filling the upper 1 m of soil, with a lateral spread of around 0.75 m on all sides and a maximum depth of around 1 m reached by the main taproot as well as downward extension of lateral root branches (Weaver and Bruner, 1927). These are just three different plants; each plant has specific rooting habits and growth patterns that affect the soil in different ways.

Thus, the presence of a healthy root system may affect pressure transfer from surface loading, although this was not a focus of this study. A hypothesis could be presented, predicting that if a healthy root system was in place (or had been place, if the crop had just been harvested), less pressure would be transferred to shallower depths in the soil than if there was no root system in place at all.

Another difference between reality and the experimental field environment is that subsoiling was not performed in the field plots. This would have been impossible because of buried instrumentation within plots. Not all farmers subsoil often, so the exclusion of subsoiling was considered to be a reasonable decision.

Although soil management of the field during the experiment was designed to be representative of normal farming, it could be seen to have some similarities to a controlled-trafficking (CT) scheme. It may be viewed as a 'worst-case' scenario of conventional non-CT farming, given the repeated vehicle and wheel passes over the same ground.

4.4.3 Choice of Cultivation Method

Another aspect of the soil management within this field study is the use of different cultivation schemes on each of the four field plots. At the outset of the study, it was not known how the different cultivation schemes would affect the pressure transfer to buried objects, but it was hypothesized that the use of inversion tillage would yield higher magnitudes of pressure transfer in their respective plots. The premise of this hypothesis was that the inversion and overall disturbance of the ploughed soil would weaken the soil, and thus allow the pressure to penetrate more easily and deeply through the soil profile.

Each cultivation method has a different effect on the soil profile, due mainly to differences in the depth of soil disturbance.

In this study, the working depth of the inversion plough was 250 mm, and the shallow plough 125 mm. A ploughed soil typically has an open and weak structure within the inverted layer (250 mm / 125 mm), followed by a more compact layer and then what can be considered the natural structure of the soil within the deeper parts of the soil profile.

The drilling operation following tillage breaks down clods further with tines and disks. This creates a finer tilth for seed germination. The subsequent rolling operation recompacts the lifted, loosened, and broken soil so that it retains moisture for seed germination. The rolling operation also ensures that once the seeds do germinate, the soil has a sufficient density to anchor the growing crop.

Sometimes a layer of compacted soil forms just below the level of the cutting edge of the plough share. This is called a 'plough pan', and occurs because this soil is not loosened. Depending on the moisture content of the soil during ploughing, the bottom edge of the plough share may also smear the top of the cut surface of soil as it passes, blocking soil pores and creating a barrier to water infiltration and sometimes even root passage. This layer of soil also interacts with the weight of passing vehicles or tillage operations, as the ploughed layer of soil may not fully support loadings.

Non-inversion tillage (this study used a Simba Solo unit drawn by a large tractor) has a disturbance depth of 125 mm, and does not flip or invert the top layer of soil. Instead, it uses a combination of tines, disks, and DD rolls[3], to loosen, cut, and re-pack the soil, preparing the seed bed. The tillage implements are arranged in a long frame, and pulled in-line with each other through the soil. The resulting tilth contains smaller clods compared with a ploughed soil, and generally remains stratigraphically distinct from deeper soil layers. The crop residues (above and below-ground biomass included) are cut up and semi-incorporated into the soil, and finally pressed down. A soil tilled in this way typically has smaller clods and a gently pressed surface, but remains uncompacted and is ready for seeding. The top 125 mm of soil is weak, but the soil underneath it retains its natural structure.

As there is a layer of weaker soil over which other vehicles pass, including the drilling machine and the rolling operation directly after tillage, some compaction can occur.

With zero tillage, some kind of tillage implement may be used minimally to break the surface and allow for seeding, but this will be the only 'opening' of the soil. In this study the drilling operation was followed by the rolling operation to ensure a packed tilth.

As the structure of the soil remains intact, the soil will be stronger and better able to support heavier loads. Less pressure will be transferred through the soil overall, which could protect buried objects. If the soil is ever loaded to the point where large amounts of deformation occur (if it was too wet for example) both at the soil surface and deeper in the soil profile, the load will be carried to deeper levels of the soil profile. Then, hard-to-reverse deep compaction could affect water and nutrient movement. Depending on the depth of the deep compaction it may be possible to loosen the soil by subsoiling; however, if the compaction is deeper than the reach of the subsoiler, serious damage will have been caused to the soil profile. Thus, if a zero tillage cultivation scheme is chosen, great care should be used to avoid overloading the soil and/or

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3  As displayed, a set of double-press rolls utilized for deeper consolidation of worked soil. Image from http://www.simbaconsolidationsystems.co.uk/600mm.html

travelling on it during adverse soil conditions. In this way, a sustainable long term soil health will be preserved.

Different cultivation regimes can be expected to result in different subsurface pressures. A zero till cultivation scheme leads to a more connected, structured, and resilient soil profile. This mature soil structure is able to reduce the depth of pressure transmission better than the soil profile created by non-inversion and inversion tillage (both conventional depth and shallow). The soil within the non-inversion plot is not as good at reducing pressure transmission to depth as in the zero till plot, but it does reduce pressure transfer relative to both inversion plots. The weak upper layer of soil in both inversion plots was not able to support the surface loadings as well as in the other two plots. The soil in the conventional inversion plot transmitted the highest magnitudes of subsurface pressure, followed by that in the shallow inversion plot.

These results indicate that implementation of a zero till or non-inversion system can provide a further layer of protection keeping the total measure of damage risk down for any type of buried artefact.

4.4.4 Subsurface Pressure Generation from Field Operations

Following tillage, a specific set of individual field operations, were performed on all four plots. Pressures were collected for each of these operations to assess the pressure generation properties of each field operation.

Each field operation employed specific machinery that was unique and resulted in a different interaction with the soil, producing different subsurface pressures. Each field operation is discussed individually, in terms of the general relationships between vehicle specifications (vehicle, loading, and tyre inflation pressures) and subsurface pressure generation.

The ploughing operation, used for cultivation of the inversion plot, consisted of a mid-size tractor and 4-share reversible plough, weighing together around 6.5 tonnes, using tyres and inflation pressures of 380/70 R28 at 1 bar for the front tyre and 480/70 R38 at 0.5 bar for the back tyre. Ploughing was performed to a depth of 250 mm. This field operation generated a mean peak subsurface pressure of just over 2 bar, which occurred when the tractor's wheels drove in the furrow bottom and were therefore very close to the buried sensor.

The shallow plough operation, used for cultivation of the shallow-inversion plot, consisted of a small tractor with a 2-share non-reversible plough, weighing together around 2.2 tonnes, using tyres and inflation pressures of 6.00-16 at 2 bar for the front tyres and 12.4/11-28 at 1.5 bar for the back tyres. Ploughing was performed to a depth of 125 mm. This field operation generated a mean peak subsurface pressure of 1.6 bar, again occurring when the tractor's wheels drove over the sensor in the furrow bottom.

The non-inversion cultivation operation used within this study was the Simba Solo, operating to a depth of 125 mm and utilizing a large tractor pulling a combination tillage set. This operation was performed with either a wheeled tractor or a comparable tracked tractor. When using the wheeled tractor, the tractor and tillage set together weighed around 15 tonnes. When using the tracked tractor, the tractor and tillage set together weight around 22 tonnes. However, the generated peak subsurface pressure under both the wheeled and the tracker tractor was very similar (hence a decision to interchange the two vehicles when necessary for the same job).

As there was no cultivation in the zero till plot, there is no value for a mean peak subsurface pressure.

The drilling operation followed the cultivations on all plots. This operation used a large tractor and midsize drilling system with discs, together weighing 11.5 tonnes. The cutting depth of the discs was 75 mm, and the tyres and inflation pressures varied per tractor (as different ones were on loan throughout the project), but typical of the tractor and task, *e.g.* 540/65 R30 at 1.25 bar for the front tyre and 650/65 R42 at 1.25 bar for the back tyre). This operation generated a mean peak subsurface pressure of just over 1 bar.

The rolling operation following the drill operation consisted of a midsize tractor pulling a set of Cambridge rolls. The combined weight of the tractor and rolls was about 6.5 tonnes. This tractor was unique within this project as it utilized Low Ground Pressure (LGP) tyres. The LGP tyres are a lot wider than conventional tractor tyres, and use low inflation pressures. The tyres were 400-17.5 at 0.7 bar in the front, and 66x43.0-25 at 0.6 bar for the back tyres. The mean peak subsurface pressure generated under this operation was relatively low, around 0.7 bar.

Both the Spray 1 and the Spray 2 operations were performed on all four plots using the same vehicle. This was a sprayer vehicle (not a tractor pulling a tank and sprayer), and weighed around 6 tonnes with a full tank of water. The tyres were also specific to the vehicle, all four tyres being 12.4-24 12 ply tyres inflated to 1.2 bar. The vehicle itself was lifted so that while spraying it would not harm any crop, and so it had a very high centre of gravity. The mean peak subsurface pressure generated under this vehicle was around 1.3 bar.

For some cultivation sets, as noted previously in this chapter, the harvesting operation was performed with a heavy tracked tractor to simulate the front end of the combine, which normally carries a large part of a combine's load. The results can also be compared with a small (loaded) tracked combine or a full-sized (unloaded, with a header) tracked combine, which was otherwise used for the fieldwork whenever possible. The tracked tractor used as a simulated harvester weighted 15 tonnes, and the tracked combine weighed around 23 tonnes (header weight included). The pseudo-harvester generated a mean peak subsurface pressure of around 1 bar, while the full-size harvester generated a mean pressure around 1.5 bar. Also, the peak pressures under the 'real' harvester were higher under the back wheel than under the tracks. The reason for this could be both that the harvester was not fully loaded, but it is more likely that the tracks on the front of the harvester distributed the weight of the harvester and the header along the entire length of the tracks and thus brought down the peak subsurface pressure. It is recognized that the two harvester operations were different from each other, both in the vehicles used and the subsurface pressures they generated. In the final data analysis, these harvester operations were combined and the resulting mean peak pressure of 1.3 bar. Having observed the differences between the two vehicles, it was decided that the situation should still reflect reality.

The tractor – trailer combination utilized a large tractor and a trailer, with a combined weight of around 13 tonnes (depending on the load in the trailer). The tyres and inflation pressures were typical for such an operation, with the front tractor tyre 7.5-16 8 ply at 1 bar, the back tractor tyre 13.6 R38 6 ply at 1.2 bar, and all four trailer tyres 12.5/80 x 15.3 at 2.5 bar. The inflation pressures are higher to support the high loads of the trailer. Additionally, the trailer wheels are more similar to truck tyres than agricultural ones. The mean peak subsurface pressure generated under the tractor – trailer combination was around 1.5 bar.

It is necessary to grasp the general relationships between vehicle specifications and pressure transfer in order to understand how to minimize pressure transfer in a field situation.

The major sources of subsurface pressure are vehicle mass (load), the tyre (or track) type, and the tyre inflation pressure. These three factors determine the size and character of the contact area of the vehicle with the soil surface. The vehicle's load is spread proportionately over the contact points between it and the soil surface. The contact points are generally tyres or tracks. A minimal amount of the load is supported by a tillage tool itself.

If the vehicle's mass is large, and its overall contact area is also large, the resulting pressure within the contact areas will be lower than if the same large load was supported on a small contact area. Since soil is a deformable medium, it will respond to the shape and type of tyre (which is also deformable).

No matter what size the tyre, if it is inflated to a higher pressure, the tyre will deform less when loaded. The contact area will increase somewhat, but the overall contact area will be remain limited, with a higher concentration of pressure in the centre of the tyres footprint. If the same tyre is inflated relatively less, but similarly loaded, it will flatten out, as there is less air in the tyre and the tyre walls are not able to support the load without full inflation. The contact area will be larger, wider, and longer; and, as the tyre flattens, the pressure under the entire contact area will be more evenly distributed. The average contact pressure will also be less, as there is more area supporting the load.

For a given loading, a wide-section and large-diameter tyre will have a larger contact area, with less pressure concentration in the centre of the contact area, and a lower overall contact pressure. A different, thin-section, small-diameter tyre, inflated similarly and submitted to the same load, has a smaller contact area. The overall contact pressure will be much higher, as there is a much smaller contact area over which to spread the same load.

Contact pressure at the soil surface is transmitted through the soil profile. The magnitudes of subsurface pressures are related to the contact pressures, which are affected by the vehicle specifications. The relationship between the ground pressures at the contact area and vehicle specifications with different tyre, inflation, and loading combinations, is similar to the relationship between subsurface pressure magnitudes and vehicle specifications.

Figure 4.4 presents the "Predicted means of peak subsurface pressures for field operations," with the field operations arranged in ascending order of magnitude.

The first three operations listed in the graph are the zero till cultivation, and two intermediary operations that were only used to level off the plots in the soil when absolutely necessary to ensure that the other field operations could function properly. The Pigtails operation and the ZigZag operation were both light shallow-working tillage tools, pulled by the same midsize tractor which was used for the Rolling operation (with the low ground pressure (LGP) tyres). They were accessory operations to the project.

The Roll operation, with a mean peak subsurface pressure of 0.68 bar, generated the lowest pressure. The Drill operation, generating 1.03 bar, gave the next highest pressure. The Roll and the Drill operation were different from each other. The roll operation carried a total weight of about 6.5 tonnes, with LGP tyres. The drill operation carried a total weight of 11.5 tonnes, with conventional tractor tyres at normal inflation pressures. Although the total weight of the drilling operation was higher than the roll operation, it is believed that the LGP tyres were a large factor in the large difference in subsurface pressure magnitudes from the two machines.

The Simba Solo operation is almost equal in magnitude of generated pressure by the Spray 1 operation (1.27 bar), the Harvester operation (1.30 bar), and the Spray 2 operation (1.31 bar). These operations are all very different from each other, with entirely different vehicles, loads, and track/tyre arrangements.

The Simba Solo uses a large wheeled or tracked tractor to pull a long and relatively heavy tillage set. This operation relies on a conventional-type tractor-pulling-implement vehicle arrangement. The tractor and implement combined does create a large surface load, and the load is neither concentrated within small nor spread over larger contact areas. The resulting surface pressure is thus higher than other tractor-implement combinations but not as high as, for example, the Tractor – Trailer operation.

The Spray operation used a smallish vehicle loaded with over 1 tonne of water, but was mounted with thin, relatively high-inflated tyres. It was relatively light (only weighing around 6 tonnes). However, with small, thin, and hard tyres, the contact area for the vehicle was decreased. With this smaller contact area supporting 6 tonnes, the contact pressure was raised enough to exceed that of the Simba Solo operation.

The Harvester operation used a large, heavy vehicle, but utilized tracks to elongate and expand its surface contact area. Although the harvester was the heaviest of the three operations, the peak subsurface pressure did not reflect this. The elongation of the contact area resulted in lower contact pressures and thus generated lower subsurface pressures.

The Tractor – Trailer generated a peak subsurface pressure of 1.46 bar. Its mass was about 13 tonnes, which included the truck (4.5 tonnes) and the trailer (8.5 tonnes). The reason that this operation generated such high subsurface pressures was not necessarily the loading, as it was not excessively high relative to some of the other operations. The peak subsurface pressures occurred under the trailer. It is the small, relatively thin, hard (highly inflated – 2.5 bar), and sharp-profiled tyres that affected the subsurface pressure generation. The trailer was mounted with road-ready truck-type tyres (similar to most agricultural trailers). It is due to the properties of these tyres that the subsurface pressure generation was high.

The operations generating the highest subsurface pressures were the ploughing operations (Shallow Plough and Plough, respectively low to high). The Shallow Plough operation used a small tractor, carrying only 2.2 tonnes. However, the front tyres were at 2 bar inflation and the back tyres were at 1.5 bar inflation. The Ploughing operation was also relatively light, at 6.5 tonnes, and tyre pressures of 1.5 in the front and 0.5 in the back. The Shallow Plough operation generated 1.61 bar, significantly higher than the Tractor – Trailer operation as well as all other operations (except the Plough of course). The Plough operation generated mean peak subsurface pressure of 2.04 bar, the highest pressure generation of the entire set of field operations. Both these operations were relatively light. The Shallow Plough operation was excessively light. However the Shallow Plough had high tyre pressures. The tyres mounted on the tractor involved in the Plough Operation had relatively low tyre pressures. With such low load for the Shallow Plough, and with low tyre pressures in the Plough operation, the magnitudes of peak subsurface pressures would not have been expected to be so high.

However, the ploughing operation, by nature opens a furrow into the soil profile (Shallow Plough – 125 mm; Plough 250 mm). The wheels in both operations drove within the previously opened furrow on every pass of ploughing. *This* is the reason that the subsurface pressures were so high. There was a very small amount of soil between the buried sensors and the tractor wheels, and thus, the pressures applied by the operations did not have any depth of soil through which to dissipate before affecting the buried sensor. Thus, the pressures were larger because of a physical lessening of the proximity of the loading source to the buried object. The pressure transfer dynamics through the soil provided very high peak subsurface pressures under these two operations.

From the above discussion, it should now be possible for a land manager to identify the properties of their field vehicle or operation that would intensify or weaken subsurface pressure generation. With the wide array of field operations and diversity of elements affecting pressure generation utilized within this study, it should also be easy to identify a similar operation or vehicle setup, in order to get a further idea of the magnitudes of subsequent subsurface pressure generation.

4.4.5 Long-term Effects of Field Study on Soil Status

The field plots were left to rest between the intense data-collection cultivation periods over the 3-year term of this project (from set-up to take-down). The intention of this resting period was to allow the soil time to rest and recover. In the spring cultivations the soil was left 'closed', as if it had just been planted (the last operation passing over the soil was the Tractor – Trailer combination). This left the soil in a similar condition to that before a normal spring planting cycle. In 2006, after the autumn cultivations in the second year of the experiment, the soil was left 'open' (just cultivated) because the soil had become too wet. After the autumn cultivation in 2007, the field soil was left 'closed' in order mimic the normal winter season cultivation/cropping pattern.

The four plots, having been cultivated differently, all 'aged' differently through the course of the study.

The inversion (ploughed) plot developed a weak-structured upper 250 mm of soil. This became visible after the first cultivation period, and became more obvious as the 5-year sets of cultivation 'years' were continued over the course of the study. Generally, after the first two 'years' of the cultivation sets (two ploughings), the soil became more plastic, and easily deformed. By the last (fifth) cultivation set, the small percentage of clay present in the soil actually brought sheen to a rubbed soil surface. It was obvious that the soil was overworked, yet large clods still remained. After the summer or winter for a soil-resting period, the subsequent first ploughing operation turned over soil that resembled in appearance and feel to the first-plough soil from the previous cultivation set. It was not possible to know whether the soil had truly restructured during the resting period; however, there were signs that the resting period had allowed the soil to regain at least some of its former integrity.

The soil in the shallow inversion (shallow plough) plot resembled that from the inversion plot, except that the disturbed soil layer was 125 mm deep. The structure of the shallow ploughed soil however did not seem as degraded as the ploughed soil. It did not feel as plastic, nor did it always have a sheen when rubbed. This could be due to the use of a smaller and lighter vehicle and implement, as well as a shallower working depth. As in the plough plot, the soil seemed to regain its integrity after some months rest.

The soil in the non-inversion plot seemed to sustain the sets of multiple cultivations. In particularly wet or humid cultivation periods it would get a bit sticky and the DD rings on the Simba Solo would sometimes get clogged with soil (so the plot was left to dry before continuing). This small intervention seemed to help the soil remain workable in the face of such intense multiple cultivations. It held up without becoming too consolidated during field operations and seemed to recover to a certain extent during the resting periods.

The soil in the zero till plot was harder to observe, as the plot was never cultivated to any depth (aside from the discs in the drilling machine, nothing broke its surface). As the soil surface did not submit to deep rutting or cracking, it could be assumed that the soil under the surface remained in its natural state, retaining structure and integrity throughout the entire experimental period. One observation however, was that the soil surface itself seemed a bit harder. This may have been due to the lack of cropping on the plot. A cropped soil may not have exhibited such a hard surface, as the plant roots and stalks would have penetrated the upper layers of the soil, loosening the soil.

The above are all made from visual and tactile observation over the course of the experiment by the author. A more quantified evaluation of soil physical status was not included within the scope of this experiment. If performed, possible ways to quantifiably evaluate long-term soil health could be based on biological sampling. It could also be a study based on crop yield after the field is re-commissioned to a normal farming cycle, with a plot generating a lower crop yield indicating some long term negative effects of the intense field operation sets that all plots were submitted to within this study.

4.4.6 Ability to Mimic 'Real-life' within Field Research

There will always remain the question of how well this experiment was able to mimic what may have happened in a real-time and real-life scenario. This accelerated experimental design incorporated very intense soil treatment, and thus may have affected the way that the pressure transfer occurred through the soil profile onto the buried sensors.

One way to attempt an answer to this question could be an auxiliary data analysis focusing on the peak subsurface pressure magnitudes to determine whether or not they seemed to increase or decrease relative to the length of study duration. If the peak pressures progressively increased or decreased this could indicate some change in overall soil properties that might not have happened outside of an accelerated experiment. In practice however, this is not feasible.

Soil physical properties are sensitive to changes in moisture content; a wetter soil will behave very differently from a dry soil. Because the range of observed moisture contents was relatively large, the median value was chosen to serve as a covariate test in the statistical analysis of the field pressure data. This showed no significant difference resulting from seasonal changes in moisture content.

If the aim of the investigation changed to investigate the overall effect of passing time on pressure transfer magnitudes, the statistical analysis would have needed to be changed. The analysis would have needed to use the peak pressure values from each accelerated-year (not cultivation set means), grouped by moisture content, and analyzed for variance relative to the passage of time.

4.5 Conclusions

This fieldwork study presents a rigorous collection and analysis of peak subsurface pressures generated under conventional agricultural field operations. These results provide a sound description of the subsurface pressure magnitudes that can be expected under conventional, contemporary agricultural operations.

The field trials were aimed at measuring and recording subsurface pressures within a 'real' environment. The methods utilized within this study succeeded in allowing a vast amount of good-quality data to be collected, allowing confidence to be placed in the results.

Key conclusions relate to differences in magnitudes of generated subsurface pressures within soil cultivated by either inversion, shallow inversion, non-inversion or a zero till treatment.

The field operations within the inversion plot generated the highest subsurface pressures, followed by those in the shallow inversion plot, the non-inversion plot, and the zero till plot. The zero till cultivation scheme would be the best choice in a strategy to lower overall peak subsurface pressures (that could harm buried archaeology).

Three factors had the largest influence on the magnitude of the generated pressure. The mass of the vehicle or operation, the tyre or track type, and the tyre inflation each influenced the overall magnitude of the pressure transfer.

The operations within this study that generated the highest subsurface pressures were the inversion (plough, shallow plough) cultivation operations and the tractor – trailer. Both ploughing operations involved the tractor driving in the open furrow bottom, which greatly increased the subsurface pressure at depth. The tractor – trailer operation caused a higher subsurface pressure due to the high load and small, thin, highly-inflated tyres.

The spray operations (both 1 and 2) generated a very similar peak subsurface to the harvester operation and the simba solo operation. The spray vehicle was very light, but generated the same subsurface pressure as the harvester because of its thin wheels and highly-inflated tyres. The simba solo operation involved a large tractor and a heavy tillage train, so the factors involved in this loading scenario were the higher load combined with average tractor tyres and inflation pressures. The harvester operation was heavier than the simba solo operation, so it could have generated higher peak subsurface pressures. However, the use of a track instead of a tyre system greatly reduced the peak subsurface pressure generation, allowing it to generate as little subsurface pressure as the sprayer or the simba solo.

The drilling operation used a lighter tractor and drill kit than what was sustained for the simba solo operation. Naturally, the peak pressure under the drill operation was lower. The rolling operation generated the lowest peak subsurface pressure of the other main field operations. The loading and rolling kit had a similar mass to that of the drilling operation, but the tractor pulling the rolls was using LGP tyres. The wide tyres and low inflation pressures reduced the generation of subsurface pressure.

The results of this study will allow a farmer or land manager to understand their usage of field operations and the subsequent effect that each operation may have on the soil status. As this study was performed with complete range of field operations, it allows comparison of similar types of vehicles and machinery to those presented here. With further knowledge of subsurface pressure generation relative to the soil status, better field management will ensue, enabling better protection of buried artefacts.

Chapter 5: Predicting Artefact Damage from Field Operations

5.1 Introduction

A main aim of this research was to develop a method for predicting damage to buried artefacts from subsurface pressures generated by surface loads from conventional agriculture. This section links the laboratory breakage thresholds found in Chapter 3 with the subsurface pressures generated under field operations presented in Chapter 4. The 'model' proposed is able to identify the breakage thresholds for specific types of buried objects. It reveals the field operations that should not damage buried archaeology, and warns of those field operations that could potentially damage buried archaeology.

Generally, the concept of a threshold refers to a level below which something will not happen and above which something will happen (or vice versa). This level is usually one value (with or without error boundaries), which supports a decision about whether a threshold has been exceeded. The thresholds within this study however are ranges of subsurface pressure levels corresponding to a 0-100% proportion of broken buried objects. This yields information on how a population of buried artefacts and/or individuals within a population, will respond to surface loading. Each object has a distinct subsurface pressure threshold range. For buried objects that consistently break at similar subsurface pressure levels or whose materials are more homogeneous, the threshold range will be small; whereas, for buried objects having different areas (rim, body, bottom) breaking under different pressure or having a more heterogeneous material makeup, the threshold range is larger.

The actual results from this study are strictly applicable to the materials studied, as they rely on an empirical prediction model. This prediction model could be used appropriately for brittle ceramic artefacts believed to have similar material properties, shapes, sizes, and burial orientations to those used in this research. In principle, the thresholds might be estimated by physical modelling, but given the variable material properties and forms of artefacts, an empirical approach is more appropriate. For ceramic, brittle objects, such a model might come close to representing real-life; but, due to the nature of the model, it would be inherently idealized. And a deterministic model would not be at all suitable for object types like metal, wood, and other organic materials. This is because the preservation, physical, and chemical states of these object types are almost always affected by surrounding soil chemistry, moisture status, and other external factors. These objects are not chemically inert, they are not brittle, and their material strength and other mechanical properties will always be different from case to case. Unfortunately, at this time there is insufficient knowledge about buried artefact behaviour, breakage dynamic, and material strength properties to create an accurate deterministic model.

This research has included experimental work within a sandy loam soil. There is much known about other soil types and pressure propagation within soils. However, the specifics of this work require knowledge of smaller magnitudes of pressures within the topsoil profile on specific sizes of objects (*i.e.* small artefacts) as opposed to soil-soil stresses or larger stresses on large underground installations. There is also the issue of soil type having an effect on the integrity of the buried artefact (as mentioned in the previous paragraph) that would affect the breakage dynamics and threshold. Hence, the focus of this study is on predicting damage within a sandy loam soil for ceramic and bone materials.

5.2 Methods

The prediction function used to link the laboratory breakage threshold ranges to the subsurface pressures under field operations originates from an equation in the statistical analysis of the laboratory breakage trials (Chapter 3). This logit equation evaluated the breakage data of the buried objects relative to the probability of their survival under subsurface pressures generated by subsurface loading. This inherently allows breakage prediction of the same objects relative to other subsurface pressures outside of those generated within the laboratory breakage trials.

The prediction function requires an input subsurface pressure value corresponding, for example, to a chosen field operation, for which it will produce a prediction of percentage of object breakage. The user can then assess the acceptability of predicted damage in relation to the relative value of the artefact and the intended field operation; appropriate field-soil management decisions may be made. The interactive nature of this empirical prediction tool empowers the user by allowing them to make the final valuation assessment of the potential implications for buried artefact damage by surface traffic.

The logistic regression between artefact breakage and subsurface pressure is based on the dataset of laboratory breakages and field subsurface pressures recorded within this study. The statistical and mathematic theory and calculation of the Logit regression has been presented in Chapter 3. The subsurface pressure data corresponding to field operations used in this correlation is the dataset from Chapter 4.

Each dataset was originally in a different format. The laboratory data consisted of peak subsurface pressure levels per run in the soil bin before and after the electric circuits surrounding the buried pots and bones indicated breakage. As these laboratory breakages most resemble a 'survival' dataset, they were dealt with in a way that utilized their variability but still took advantage of the information contained in the data. The field data were peak subsurface pressure values generated under a set of conventional field operations.

In Chapter 3 the laboratory breakage dataset was transformed by a logistic regression, which yielded the prediction function that will be used here to correlate the two datasets. Since this prediction function was created from the laboratory breakage data, it is not necessary to maintain the original dataset for the correlation. For the correlation exercise, the prediction function used the field dataset, which consisted of the summarized peak subsurface pressures recorded under a range of conventional field operations. The field data served as the subsurface pressure input 'χ' value, and the prediction function yielded a number between 0 and 100 indicating the resulting percentage of breakage predicted to occur. In this way, it was possible to evaluate damage potential for any input subsurface pressure corresponding to a specific field vehicle or operation, relative to the pots and bones used as pseudo artefacts in this research study.

The prediction function, as noted in Chapter 3 is presented in Equation 1, and is used with appropriate inputs (input subsurface pressures for χ -value and using the different β-beta and α-alpha factors specific to each object type).

Equation 1 (Equation 1 from Chapter 3, simplified for use here in Chapter 4)

Prediction Function

Used to solve for P, using the β (slope) and α (intercept) factors
(see Chapter 3; these factors correspond directly with a specific object type):

$$P = (100 * \exp(\beta * \chi + \alpha)) / (1 + \exp(\beta * \chi + \alpha))$$

The results of the breakage prediction study are displayed and explained in the Results and Discussion section of this chapter, respectively.

5.3 Results

The prediction function was calculated for all field operations relative to all object types. The mean peak subsurface pressures from each field operations were used as the χ-value pressure input in the prediction function. The values for the β-beta and α-alpha factors were specific to each object type.

Table 5.1 presents the outcome of this prediction exercise for the *ceramic pots* used in this study; Table 5.2 presents the prediction outcome for the *aged bone* used in this study.

Table 5.1: Pot breakage prediction table, indicating percentage of object broken if submitted to field operations.

Subsurface pressure = bar breakage estimation unit = %	(S.E. n/a)	Reference Pressure	(S.E. n/a)	*Minus* S.E. of 0.12	Reference Pressure	*Added* S.E. of 0.12	*Minus* S.E. of 0.18	Reference Pressure	*Added* S.E. of 0.18
Prediction function input	**0**	**0**	**0**	**0.31**	**0.43**	**0.55**	**0.29**	**0.47**	**0.65**
Operation type → **↓ Pot type**		**1. Nothing**			**2. Pigtails**			**3. ZigZag**	
Shell tempered: Rim	0	0	0	0	0	0	0	0	0
Shell tempered: Body	0	0	0	0	0	0	0	0	0
Grog tempered: Rim	0	0	0	0	0	0	0	0	0
Grog tempered Body	0	0	0	0	0	0	0	0	0
Flint Tempered: Rim	0	0	0	0	0	0	0	0	0
Flint Tempered: Body	0	0	0	0	0	0	0	0	0
Quartz tempered: Rim	0	0	0	0	0	0	0	0	0
Quartz tempered: Body	0	0	0	0	0	0	0	0	0

Subsurface pressure = bar breakage estimation unit = %	*Minus* S.E. of 0.04	Reference Pressure	*Added* S.E. of 0.04	*Minus* S.E. of 0.04	Reference Pressure	*Added* S.E. of 0.04	*Minus* S.E. of 0.08	Reference Pressure	*Added* S.E. of 0.08
Prediction function input	**0.63**	**0.68**	**0.72**	**0.99**	**1.03**	**1.07**	**1.14**	**1.21**	**1.29**
Operation type → **↓ Pot type**		**4. Roll**			**5. Drill**			**6. Simba Solo**	
Shell tempered: Rim	0	0	0	38	55	70	88	97	99
Shell tempered: Body	0	0	0	0	0	0	0	0	0
Grog tempered: Rim	0	0	0	0	0	0	0	0	0
Grog tempered Body	0	0	0	0	0	0	0	0	0
Flint Tempered: Rim	0	0	0	1	1	1	2	3	4
Flint Tempered: Body	0	0	0	0	0	0	1	1	1
Quartz tempered: Rim	0	0	0	0	0	0	0	0	0
Quartz tempered: Body	0	0	0	0	0	0	0	0	0

Subsurface pressure = bar breakage estimation unit = %	*Minus* S.E. of 0.04	Reference Pressure	*Added* S.E. of 0.04	*Minus* S.E. of 0.04	Reference Pressure	*Added* S.E. of 0.04	*Minus* S.E. of 0.04	Reference Pressure	*Added* S.E. of 0.04
Prediction function input	**1.23**	**1.27**	**1.31**	**1.26**	**1.3**	**1.33**	**1.27**	**1.31**	**1.35**
Operation type → **↓ Pot type**		**7. Spray 1**			**8. Harvester**			**9. Spray 2**	
Shell tempered: Rim	98	99	99	98	99	100	99	99	100
Shell tempered: Body	0	0	1	0	0	1	0	1	2
Grog tempered: Rim	0	0	1	0	0	1	0	1	2
Grog tempered Body	0	0	0	0	0	0	0	0	0
Flint Tempered: Rim	3	4	4	3	4	5	4	4	5
Flint Tempered: Body	1	1	1	1	1	1	1	1	1
Quartz tempered: Rim	0	0	0	0	0	0	0	0	0
Quartz tempered: Body	0	0	0	0	0	0	0	0	0

Subsurface pressure = bar breakage estimation unit = %	*Minus* S.E. of 0.04	Reference Pressure	*Added* S.E. of 0.04	*Minus* S.E. of 0.17	Reference Pressure	*Added* S.E. of 0.17	*Minus* S.E. of 0.2	Reference Pressure	*Added* S.E. of 0.2
Prediction function input	**1.42**	**1.46**	**1.5**	**1.44**	**1.61**	**1.78**	**1.83**	**2.04**	**2.24**
Operation type → **↓ Pot type**		**10. Tractor / Trailer**			**11. Shallow Plough**			**12. Plough**	
Shell tempered: Rim	100	100	100	100	100	100	100	100	100
Shell tempered: Body	37	74	93	55	100	100	100	100	100
Grog tempered: Rim	37	74	93	55	100	100	100	100	100
Grog tempered Body	3	11	38	5	98	100	100	100	100
Flint Tempered: Rim	7	8	10	7	15	27	33	55	76
Flint Tempered: Body	2	2	3	2	4	8	10	20	36
Quartz tempered: Rim	0	0	0	0	0	0	0	0	0
Quartz tempered: Body	0	0	0	0	0	0	0	0	0

The function predicts the resultant breakage for three subsurface pressure χ-value inputs per operation: the mean peak subsurface pressure is used as the reference pressure, and the values of this reference pressure +/- the standard error. The field operations are numbered for clarity and presented in ascending order of magnitude of mean peak subsurface pressure (bar) from left to right, top to bottom. S.E. values are also shown.

Table 5.2: Bone breakage prediction table, indicating percentage of object broken if submitted to field operations.

Subsurface pressure = bar breakage estimation unit = %	(S.E. n/a)	Reference Pressure	(S.E. n/a)	Minus S.E. of 0.12	Reference Pressure	Added S.E. of 0.12	Minus S.E. of 0.18	Reference Pressure	Added S.E. of 0.18
Prediction function input	0	0	0	0.31	0.43	0.55	0.29	0.47	0.65
Operation type → ↓ **Bone type**		1. Nothing			2. Pigtails			3. ZigZag	
Perpendicular: Bottom	0	0	0	0	0	0	0	0	0
Perpendicular: Top	0	0	0	0	0	0	0	0	0
Parallel: Bottom	0	0	0	0	0	0	0	0	0
Parallel: Top	0	0	0	0	0	0	0	0	0
Subsurface pressure = bar breakage estimation unit = %	Minus S.E. of 0.04	Reference Pressure	Added S.E. of 0.04	Minus S.E. of 0.04	Reference Pressure	Added S.E. of 0.04	Minus S.E. of 0.08	Reference Pressure	Added S.E. of 0.08
Prediction function input	0.63	0.68	0.72	0.99	1.03	1.07	1.14	1.21	1.29
Operation type → ↓ **Bone type**		4. Roll			5. Drill			6. Simba Solo	
Perpendicular: Bottom	0	0	0	0	0	0	0	0	0
Perpendicular: Top	0	0	0	0	0	0	0	0	0
Parallel: Bottom	0	0	0	0	0	0	0	0	0
Parallel: Top	0	0	0	0	0	0	0	0	0
Subsurface pressure = bar breakage estimation unit = %	Minus S.E. of 0.04	Reference Pressure	Added S.E. of 0.04	Minus S.E. of 0.04	Reference Pressure	Added S.E. of 0.04	Minus S.E. of 0.04	Reference Pressure	Added S.E. of 0.04
Prediction function input	1.23	1.27	1.31	1.26	1.3	1.33	1.27	1.31	1.35
Operation type → ↓ **Bone type**		7. Spray 1			8. Harvester			9. Spray 2	
Perpendicular: Bottom	0	0	0	0	0	0	0	0	0
Perpendicular: Top	0	0	0	0	0	0	0	0	0
Parallel: Bottom	0	0	0	0	0	0	0	0	0
Parallel: Top	0	0	0	0	0	0	0	0	0
Subsurface pressure = bar breakage estimation unit = %	Minus S.E. of 0.04	Reference Pressure	Added S.E. of 0.04	Minus S.E. of 0.17	Reference Pressure	Added S.E. of 0.17	Minus S.E. of 0.2	Reference Pressure	Added S.E. of 0.2
Prediction function input	1.42	1.46	1.5	1.44	1.61	1.78	1.83	2.04	2.24
Operation type → ↓ **Bone type**		10. Tractor /Trailer			11. Shallow Plough			12. Plough	
Perpendicular: Bottom	0	0	0	0	0	0	0	0	0
Perpendicular: Top	0	0	0	0	0	0	0	0	0
Parallel: Bottom	0	0	0	0	0	0	0	0	0
Parallel: Top	0	0	0	0	0	0	0	0	0

The bone breakage threshold is never breached, as all field operations generated pressures below the lowest point of bone breakage (2.84 bar, perpendicular). The function predicts the resultant breakage for three subsurface pressure χ-value inputs per operation: the mean peak subsurface pressure is used as the reference pressure, and the values of this reference pressure +/- the standard error. The field operations are numbered for clarity and presented in ascending order of magnitude of mean peak subsurface pressure (bar) from left to right, top to bottom. S.E. values are also shown.

Figure 5.1 presents the results in a different format in order to highlight a 'worst case scenario'. It uses the prediction function for the pots, as the peak subsurface pressure according to the prediction function corresponding to the lowest 100% breakage level of all the pots – the shell-tempered pot – is displayed. The bone breakage threshold does utilize the prediction function, for reasons discussed in Chapter 3, and instead uses the lowest breakage value recorded within the laboratory study.

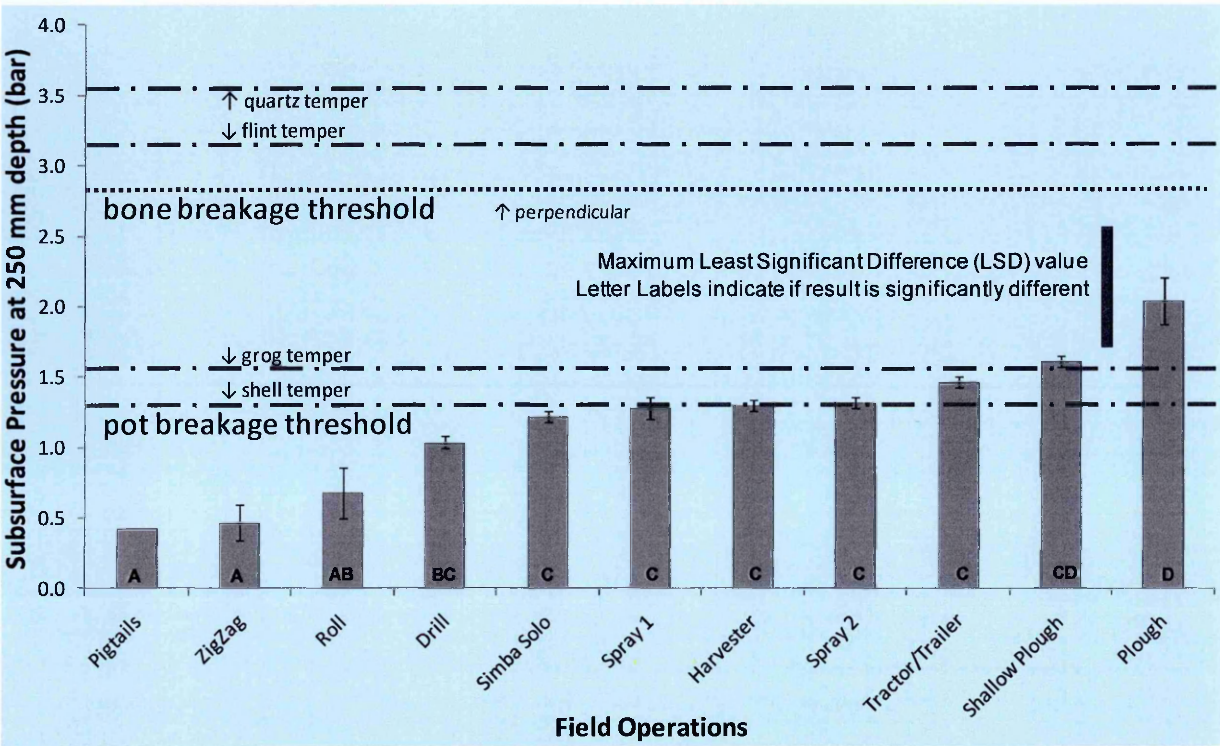

Figure 5.1: The minimum 100% breakage threshold (dashed lines) for both pot and bone artefacts in relation to predicted means of peak subsurface pressures from field operations.

Note there is no breakage threshold for the parallel orientated bone, as breakage did not occur in the laboratory study.

5.4 Discussion

The results from this correlation of laboratory and fieldwork can be discussed in different ways. There is an interest in evaluating the results relative to soil moisture and soil type. The results of the correlation of object breakage to field operation subsurface pressures must also be addressed. The use of this type of prediction model needs to be discussed relative to its value versus an equivalent deterministic/mathematical soil-object-pressure model. Finally, the minimum breakage thresholds will be related to worst case scenarios that are useful to know for the protection of buried artefacts.

5.4.1 Soil Moisture and Soil Type

Soil moisture content is a source of variability in this research. It has not been directly given a physical influence factor within the prediction model since it was measured and included in the data analysis of the fieldwork pressure results and was not an issue within the soil bin labwork (as it was controlled at a constant level). The effects of moisture content changes on subsurface pressure generation were evaluated within the fieldwork portion of the research, and its effects were considered minimal. The moisture content variation was not found to be a cause of a significant change in how subsurface pressure was generated under field operations. The reasons for this could be varied; however, some explanations could be that the field soil type had the ability to be worked over a large range of soil moisture. The field sandy loam soil has high mineral and low clay content, which allows the soil to stay in a similar physical state throughout a larger range of soil moisture. Being a mineral soil (versus an organic/peat soil), the amount of organic matter present in the soil was not enough to alter the physical aspects of the soil when wetter or drier. It is also possible that any effect the moisture status had on generated subsurface pressures was smaller than the variation of the pressure sensors or variation between field operations, and thus, would remain too small to consider significant.

Although there is no significant effect of changes in moisture content through the various working conditions of the sandy loam soil used in this research, it remains a factor that is known to have an effect on soil strength. These differences would probably have become obvious in extremely wet or extremely dry conditions. In extremely wet conditions, the soil would be less strong, and deeper cultivation and wheel/track sinkage would occur. This would bring the wheels/tracks/load-bearing portions of field kit physically closer to any buried artefacts, and the generation of the subsurface pressure would change, affecting deeper levels of the soil profile at higher magnitudes of pressure. In extremely dry conditions, the soil would be stronger, and thus better able to ‘hold up’ a vehicle or tillage tools that might be drawn over/through it. If the upper levels of the soil profile were very dry, but the lower levels of the soil profile were still relatively wet, irreversible soil compaction/deformation or buried artefact damage (as the objects themselves would retain the same breakage thresholds) could be caused at deeper levels. This discussion is important, as vehicle specifications that would under normal conditions have little potential to damage buried artefacts, could become damaging in wet conditions.

Soil type variation also is also expected to cause changes in pressure transfer onto buried objects; however, the experiments within this research were conducted only in the sandy loam soil type. Taking indication from previous research as well as parallel research done within the

Oxford Archaeology study (see Appendix F), a different soil type would have an effect on pressure transfer through soil. These increases or decreases would then have a secondary effect on the breakage of buried artefacts relative to each artefacts breakage threshold and the magnitude increase or decrease of peak subsurface pressures for any field operation.

The discussion of soil type and how it affects pressure transfer through soil must address the mechanical soil dynamics, especially those resulting from soil texture and organic matter content, which are not discussed here. This chapter addresses moisture content, different soil loading cases, and different pot types, all relative to how variations of each might protect or damage buried artefacts more or less, and all external factors that might modify or manipulate the pressure transfer within a soil type.

5.4.2 Prediction of Buried Artefact Breakage from Field Subsurface Pressures

Table 5.1 shows the predicted pot breakage per type of pot and per type of field operation, while Table 5.2 shows the same for the bones versus field operations.

The results displayed in Table 5.1 can be evaluated relative to both pot type and operation type. There are four pot types, each with two zones of breakage (the rim and the body). There are 12 different field operations, each displayed with three pressures (the mean pressure from that operation, two other values calculated from the addition and subtraction of the SE).

The pot types are organized in ascending order of resistance to breakage (ascending order of magnitude of the breakage thresholds for the most susceptible break zone within any pot type). The field operation subsurface pressures are organized in ascending order of magnitude. The most susceptible pot type to breakage relative to the field operations was the shell tempered.

Shell tempered pot type:

> The shell tempered pot type exhibits rim breakage at an earlier point than body breakage. The field operation where it exhibits first signs of breakage is under the Drilling operation. This operation consisted of a larger medium to heavy tractor with conventional wheel inflation pressures pulling an average seed drilling implement. The mean peak subsurface pressure recorded under this operation is 1.03 bar (SE of 0.04). At the reference pressure, the rim section of the shell tempered pot is predicted to have sustained 55% damage. The body is indicated to remain intact.
>
> The next operation is the Simba Solo, which yielded a mean peak subsurface pressure of 1.21 bar (SE of 0.04). Under this subsurface pressure, the shell tempered pot rims are predicted to show a 97% breakage. This indicates that almost 100% of the pot rim is broken.
>
> It is not until the Spraying and Harvesting operations that the shell tempered pot body is predicted to break. Commencement of breakage is possible under the Spray 1 and the Harvester operations, if the SE (0.04 for both) is added to the mean reference peak subsurface pressure. Under both of these operations with the SE value added to their reference pressure value, the shell tempered pot body is predicted to have 1%

breakage. At the Spray 2 operation, the reference peak pressure of the operation yields breakage of the pot body of 1% (the pot rim is now exhibiting breakage of 99%).

Under the Tractor / Trailer operation, the shell tempered pot rim is shown to sustain 100% breakage at the reference pressure of 1.46 bar. The shell tempered pot rim can now be considered fully broken. The shell tempered body breakage level has increased to 74% (with 37% under the reference pressure minus the SE, and 93% breakage under the reference pressure with added SE).

Under the Shallow Plough operation, the shell tempered body is predicted to have 100% breakage at the reference pressure level, however, the SE of the pressure is large and it is probable that the percentage of breakage could be much less.

The shell tempered pot exhibits full rim and body breakage of 100% for all reference pressure values plus and/or minus the SE values for the Plough operation, where the reference pressure is 2.04 and the SE is 0.02.

In order to protect the shell tempered pot, a threshold value would have to be chosen relative to breakage amount and operation type, which of course would be a subjectively chosen value that would depend on the proportion of pot survival necessary to consider it protected.

Grog tempered pot type:

The pot type predicted to exhibit full breakage after the shell tempered pot and under slightly higher peak subsurface pressures is the grog tempered pot.

This pot does not exhibit any breakage until the Spray 1 and the Harvester operation, and then only at the '+SE' level (showing 1% breakage of the rim only 5% of the time).

The grog tempered pot however shows breakage under the reference peak subsurface pressure under the Spray 2 operation (1.31 bar), where 1% of the pot's rim is predicted to have broken.

The Tractor / Trailer operation, with its higher reference pressure of 1.46 bar however, shows breakage of both the rim and body zones of the pot. The reference pressure produces 74% breakage of the rim and 11% breakage of the body. The SE value is 0.04, which although small, has a large effect on the breakage prediction. At the '-SE' level, the rim has a 37% breakage prediction while the body has 3% breakage prediction. At the '+SE' level, the rim has a 93% breakage prediction while the body has a 38% breakage prediction.

The Shallow Plough operation shows further breakage. The grog tempered pot rim is predicted to have broken fully - 100% - at the reference pressure of 1.61 bar. The grog tempered pot body is predicted to have broken 98% at the reference pressure, while the '-SE' pressure value produces a 5% prediction and the '+SE' value produces a 100% prediction.

Under the Plough operation, both the grog tempered pot rim and the body are predicted to break fully (100%) all of the time (for all reference pressure, '-SE' and '+SE' values).

Again, in order to protect the grog tempered pot, a threshold value would have to be chosen relative to breakage amount and operation type, which depends on a subjectively chosen value relative to the need to protect the pot.

Flint tempered pot type:

The flint tempered pot exhibits predicted breakage but does not ever fully break under the agricultural field operations within this study. It does however, exhibit partial breakage at a low level under more than half of the field operations.

The first point that breakage is predicted is under the drill operation. Here, the reference mean peak subsurface pressure is 1.03 bar (SE 0.04). The flint tempered pot (rim only) is predicted to have 1% breakage under the drill operation.

The Simba Solo operation follows, with a reference pressure of 1.21 bar and an SE of 0.08. The flint tempered rim exhibits 3% breakage here, while the pot body is predicted to have 1% breakage.

Under the Spray 1, Harvester, and the Spray 2 operations, the rim shows 4% breakage and the body 1% breakage under the reference pressure of 1.27 bar (SE of 0.04).

The Tractor / Trailer operation, with a reference pressure of 1.46 bar, shows the flint tempered rim with 8% breakage and the body with 2% breakage.

The Shallow Plough shows a 15% rim breakage and a 4% body breakage at 1.61 bar subsurface pressure (0.17 SE).

The Plough operation begins to higher levels of breakage. The subsurface pressure is 2.04 bar, and at this level, the flint tempered rim exhibits 55% breakage and the body exhibits 20% breakage. The '-SE' level produces 33% breakage in the rim and 10% breakage in the body, and the '+SE' level produces 76% breakage in the rim and 36% breakage in the flint tempered body.

Protection of the flint tempered pot under agricultural operations may be easier, as it breaks under higher subsurface pressures. However, any threshold value will be chosen relative to how much breakage can be considered acceptable for any particular artefact type, and thus the process would still be subjective.

Quartz tempered pot type:

The pot type that has the highest breakage threshold is the quartz tempered pot. This pot never exhibits predicted breakage under any of the field operations within this study. It is proposed here that this pot type requires no special protective measures if subjected only to the field operations within this study (or some equivalent).

The results presented in Table 5.2 correlating bone breakage to the field operation peak subsurface pressures is easier to analyze because neither the perpendicular orientated bone nor the parallel orientated bone show predicted breakage under the field operations within this study. Similar to the quartz tempered pot, radius bones could probably be considered protected if only subjected to these field operations.

5.4.3 Worse-case Artefact Damage Relative to Protection Efforts

The data on laboratory breakages and field subsurface pressures presented within this chapter can be related to a minimum 100% breakage threshold for each object. This is presented visually in Figure 5.1, overlaid within the bar chart of the peak subsurface pressures recorded under the field operations with this research.

For each artefact type (pot and bone) the minimum 100% breakage threshold is displayed as a dashed line. Of all four pots, the shell tempered pot has the lowest threshold, at 1.3 bar. The grog temper pot has a higher pressure threshold, at 1.6 bar. Finally, the flint tempered and quartz tempered pots have progressively higher pressure thresholds, of 3.2 and 3.6 bar respectively. The perpendicular bone had a threshold of 2.8, and the parallel bone never broke within this study so there is no corresponding threshold. The flint and quartz pot, and the perpendicular bones all broke at thresholds that were out of range relative to the field operations within this study

The minimum 100% thresholds are presented visually to allow the reader a quick and easy evaluation of the worst-case scenarios for each artefact type and field operation. In practice, this chart could provide an indicatory guide for both the artefact types studied within this research as well as, for example, other similar pot types or ceramics.

Figure 5.1 also shows in a simple way the relationship of the peak subsurface pressures' from field operations and buried artefact breakage. It is interesting to note that there are seven field operations (Simba Solo, Spray 1, Harvester, Spray 2, Tractor / Trailer, Shallow Plough, and the Plough) which generate subsurface pressure sufficient to completely break the shell tempered pot type entirely. Four of these field operations (Simba Solo, Spray 1, Harvester, Spray 2) generate subsurface pressures that are not only very similar to each other but are also very close to the breakage threshold of the shell tempered pot. If the shell-tempered pot could be considered a 'ceramic pot-type artefact worse-case scenario,' then all these field operations would pose a threat to the artefact's survival.

The grog tempered pot, having a higher 100% breakage threshold than the shell tempered pot, is not necessarily in danger of complete breakage under the Simba Solo, Spray 1, Harvester, or Spray 2 operations, but is just above the threat from the Tractor / Trailer operation (the threshold falls just above the +SE peak subsurface pressure level). The breakage 100% threshold would be exceeded under both the Shallow Plough and the Plough operation.

Although the minimum threshold level of the perpendicular aged bone artefact in this study was higher than the maximum subsurface pressure generated under field operations, other weaker bone types might not be so robust. Therefore, the low-breakage threshold for the bone should be used with caution, as misuse of the threshold by referencing 2.8 bar in a situation involving weaker bones (relative to bone type, composition, and physical orientation to oncoming loading) could quickly lead to artefact damage.

5.4.4 Usage of Breakage Thresholds Relative to Buried Artefact Protection

This discussion of pot (and bone) breakage versus dynamic surface loading from field operations returns consistently to the question of 'what is an acceptable level of damage for any particular artefact type'; i.e. what threshold could be set (and adhered to) that would 'protect' the buried artefact?

The answer to this question is inherently subjective. The prediction model constructed in this study determines the breakage in a format where a percentage of object broken is used as an indicator of breakage; thus, it provides a breakage threshold *range* as opposed to a black/white threshold value. This range is a very valuable estimate, as it allows partial breakage to be acknowledged (reflecting reality), and it allows error estimation to be incorporated into the breakage prediction. For the breakage-pressure correlations to be used in any artefact damage mitigation strategy, it would be necessary to decide how much breakage is acceptable. Decision makers need to account for artefact value and field management / farming / cropping value when assessing if artefacts should be allowed to be put in danger. As the threshold values can be easily set and reset, they allow decision makers to modify their assessment of possible artefact damage scenarios as factors change or from site to site..

In principle, any percentage of breakage could be set. A 0% breakage threshold rule could be applied, and any field operation known to generate a subsurface peak pressure higher than the amount of pressure necessary to produce even a small crack could be prohibited. An 80% breakage threshold rule could be set, that would allow 80% of the buried artefact to break, crack, or become destroyed.

After considering the above factors, it was decided for the purpose of the analysis to choose a pot breakage threshold of 50%, appropriately chosen for two reasons. The first was that a simple 50% ratio of portion of a pot broken to unbroken allowed for an impartial analysis of damage. By drawing the line at a 50% damage point, there is no more value given to preserving a pot than there is letting it get damaged. In a field of pots which could potentially all be destroyed, with an applied protection breakage threshold of 50%, one-half of them would survive, which would probably be acceptable to both a land manager and an archaeologist (of course, this depends *what* the artefacts exactly were - here, it was assumed that he buried objects would not be of any extraordinary value). The second reason to choose the 50% threshold was because it seemed to reflect the breakage dynamics of the object, in this case ceramic pot, when viewed in the light of the results of the breakage to field pressure correlation.

Pot breakage occurs when pressure generated by the subsurface loading applies a force per unit area onto the ceramic material exceeding the material yield strength. Once the ceramic's material strength is surpassed, cracks originate in the object where the stress concentrations are highest. As the subsurface pressure grows in magnitude, the cracks will continue to propagate through the ceramic material. The direction and length of the cracks relate to the ability of the material to resist the applied pressure, thus for example, where the ceramic material may be thicker the crack propagation may stop or the crack may change direction and continue to travel through the weaker areas of the object.

From observations during excavation of the buried pots that had been subjected to the surface loading within the study, the different stages of breaking were all recorded. Slightly broken pots, broken pots, and smashed pots were all represented within this research. It was observed that in the early stages of breaking, only some main cracks occurred within the ceramic material. These cracks broke the pot into a few pieces. With further applied pressure, these pieces themselves broke down into smaller pieces until the pot became a collection of pot shards and its shape was lost.

To an archaeologist, a pot with some cracks or one broken into a few pieces could still retain its value in terms of understanding the artefact and its place in history. However, a pot that has been broken up into many little pieces is much harder to reassemble and thus understanding the artefact becomes ever more difficult (especially if soil translocation moves some of the smaller pieces away from the main area of broken pot pieces). A 50% survival of a pot could imply that the pot's pieces are maybe mid-size or larger, and thus the expectance is higher that the archaeologist could more easily understand the artefact and its historical record.

It should be noted that the type and quality of buried artefacts persisting in a field will probably influence the chosen breakage threshold. Other factors include the depth of object burial, and the condition and intact quality of the buried artefact. Is it is good condition, whole, without any cracking? Or is it already in some large pieces (or small pieces). Is it large or small? Is it known from what period the artefact is from? If so, does this date make it any more/less valuable? Are there a lot of artefacts within the field area? Or are there only a few? Are they all in the same non-broken or broken state?

Archaeologists rarely encounter non-broken buried artefacts (be it ceramic, bone, or other). This is because a lot of the objects that now persist in the soil profile originated from a previous culture's waste. Objects were thrown out already broken or broken in disposal, so whole pots or bones are rare finds, except in burial sites or cemeteries.

The decision making process for choosing a breakage threshold must take the above into account. If there were no whole artefacts, and just small pot shards or the like, the threshold might be set higher, as the danger of further damage would be lower. If there were medium size pot shards, the discussion could involve an estimation of what threshold might be chosen in order to protect the shards as they are and not break them further. If there were buried pots that were known to be relatively whole and in good condition, it could be wise to set the threshold lower, in order to save as much of the archaeological record as possible. If the area of land was known to have a high number of artefacts in average condition, the threshold could be set somewhat higher (unless this was the only known such artefact deposit). If the area had a high number of average artefacts but few in very good condition, it would be wise to set the threshold lower. There are many iterations of this same scenario, but evaluating the situation separately for different circumstances allows efficient risk management.

Using the subsurface pressures generated under the field operations within this research, the pot types can be evaluated as follows relative to a 50% breakage threshold (compared to the main reference pressure of each field operation).

> The rim of the shell tempered pot reached and surpassed a 50% breakage threshold under the Drill operation. This operation generated 1.03 bar subsurface pressure, achieving 55% rim breakage. The breakage of the shell tempered pot body exceeded the 50% threshold under the Tractor / Trailer, which generated a subsurface pressure of 1.46 bar and was predicted to produce 74% breakage.
>
> The rim of the grog tempered pot also broke to 74% under the Tractor / Trailer operation (1.46 bar), surpassing the 50% threshold. The breakage of the grog tempered pot body exceeded the threshold under a higher subsurface pressure of the Shallow Plough, which generated 1.61 bar subsurface and was predicted to produce 98% breakage.
>
> The flint tempered pot rim and body were closer in behaviour than the two pots previously discussed. The rim breakage exceeded 50% under the Plough operation, with a 55% predicted breakage under 2.04 bar subsurface pressure. The body of the pot was not predicted to exceed 20% breakage under the reference pressures of the field operations within this research (it did show a 36% breakage prediction at the +SE pressure for the Plough operation of 2.24 bar).
>
> The quartz tempered pot was evidently not in any danger of breaking under the field operations in this research, as breakage was not predicted under any operation.

Of the four types of pots included in the breakage trials of this research, three yielded breakage relative to conventional field operations, with two of them failing completely under at least one operation. The shell pot is the pot where breakage exceeding 50% was predicted under field operations that produced less subsurface pressure. The grog tempered pot and the flint tempered pot were predicted to sustain breakage over 50% under the field operations generating higher subsurface pressures (the Tractor / Trailer and Ploughing operations). The field operations that were not predicted to induce breakage in any of the four pot types were the Roll, Zigzag, and Pigtails operation, all of which were undertaken by a midsize tractor operating with low ground pressure tyres.

Since the bones did not yield any indicated breakage relative to field operations, it was not possible to evaluate them relative to a 50% threshold (there would have been 100% survival).

5.4.5 Breakage Thresholds of Other Ceramic Artefact Types

There remains a question about whether the results from this study could be used for analyzing potential damage to other types of ceramic artefacts. Many past and current cultures throughout the world have a history of using ceramic artefacts. There are however, differences between the specific types of ceramic produced in every case. The raw clay material on site, the tempering materials used for production, object production method, shape and size of the ceramic objects, decoration/glazing methods, firing methods, and firing temperatures all affect the final product, thus affecting how the ceramic object could survive and resist damage.

The experiments within this research were designed to test ceramics created to mimic specific types of ceramic artefacts found in the UK. Therefore, it is not recommended that the results of this study be taken out of this context and utilized relative to the ceramic artefacts in different parts of the world.

However, the use of these breakage thresholds and prediction model for ceramic artefacts different from the types tested here, while still within the UK, may be justified. Such an application of the prediction model would depend on the ceramic artefact in question. It would be possible to evaluate whether the new pot type could be considered similar in shape, manufacture method, material content, or size to one in this study. If similarities were noted, a breakage analysis could be performed assuming this similarity, using the prediction model based on the most similar pot type. The analysis results could then be used as an indication whether or not the new pot type could be in danger from damage by surface loading.

It is considered that the outputs from this research are broadly applicable to UK ceramic buried artefacts; therefore, it is concluded that the breakage thresholds found in this study could be applied to other similar ceramics within the UK.

5.4.6 Breakage Thresholds of Other Types of Aged, Human Bones

The bones in this study are small, long bones, and it is not possible to extrapolate the results from this research to other bone types, because there is not enough information to allow reliable predictions about how the other types of bones might break when submitted to similar loading. The only way to know how, and at what pressure threshold other bone types would fail when buried at 250 mm depth and subjected to dynamic surface loading would have been to test other bone types alongside the radii in this research. The other bone types, however, were considered too valuable to be given up for such a destructive type of testing, especially in the case of the skulls). There were other bone types considered that were not as valuable as skulls (fibula or the femur), but there were not enough surviving whole bones within the Wharram Percy collection available to this research that to have provided an intact and homogeneous set of bones for experimentation.

Some indications may be found in the relative strength of other bone types (long, short, flat, irregular) to the radius bone type used within this research. Most of the bones in the human body are long bones. The radius is a specific long bone within the human skeleton. The femur is also a long bone, but it is longer and thicker. As such, the femur is similar to the radius in structure, with a cortical (compact) bone structure along the diaphysis (main shaft) of the bone and cancellous (spongy) bone at each epiphysis (bone end). The thicknesses of the cortical bone and the general size of the articular ends in a femur is generally thicker than that in a radius, due to role the bone has within the skeleton to support larger loads of the body that a femur must carry. Because of the added size combined with added mass, the femur is stronger than the radius.

Short bones have the same basic structure as long bones but are much shorter. They are approximately as short as they are wide. An example of a short bone would be the carpal bones in the wrist. This type of bone allows for movement, while retaining some strength within a small volume. The short bones have a thin layer of cortical bone surrounding cancellous bone, and as such may be less able than long bones to withstand loading.

The flat bone type includes the scapula, rib bones, pelvic bones, as well as the skull (not exclusively). Flat bones have a shell of cortical bone, which encloses the interior area of cancellous bone. They generally do not support loading (however the pelvic bones do have weight bearing capacity), and their principal purposes are for protection (such as a shield), or a broad plate for muscles attachment. These bones would have some integral toughness due to cortical bone's laminar structure, but cannot be expected to hold up under very heavy loads, and can succumb to puncture from point loads quite easily.

Irregular bones, due to their varied shape, cannot be classified into the other bone types. They generally have a thin layer of compact bone surrounding cancellous bone. They have varied purposes. Some do support loading, some protect, and some support muscle attachment. As a varied group, they all differ in their material strength and toughness properties and cannot be generalized or easily compared with other bone types.

While it is true that the bones tested in this study were the best choice relative to the practical demands and limitations of the experiment, scientifically they were not the most diagnostic for buried aged human bone as an artefact type, nor did they yield any information that could have helped archaeologists protect other more valuable bone types (skulls for example). This is because the radii bone type is relatively strong and could be more able to survive than most bones in the body. Thus it does not yield any ability to evaluate a 'worst case scenario.' In addition, they are not a very valuable bone relative to other bone types. Archaeologist efforts to save bones are not necessarily based only on radius bones, as they would be targeting protection of skulls and other valuable pieces. Further study of other bone types relative to buried, aged bone artefacts would enhance the understanding of this dilemma. Any experiments involving other bone types would yield more data and would add further benchmark values per bone type. In addition, even if the most valuable and vulnerable bone types (skulls particularly) never become available for the destructive type of testing that this research has performed, studies with proxy materials might be possible, allowing further insight into how best to protect buried aged human skeletons.

Nevertheless, the study should be considered valuable, as the breakage properties of a buried, aged radius bone was previously unknown. This research does establish benchmark values. Also, the evaluation of bone orientation (perpendicular vs. parallel orientation to oncoming surface loading) was important, as the breakage results show that the orientation to load has a large effect on how (or whether) the bone will be in danger of breaking.

5.4.7 Prediction Model

The type of model utilized in the prediction of the buried artefact breakage from the field subsurface pressures provides a valuable empirical tool that yields information of immediate use to a farmer or land manager. Much insight is gained from the correlation exercise into possible approaches to buried artefact damage mitigation strategies.

This degree of insight comes from the amount of information that this model offers, as well as in how it can be used.

The breakage thresholds are presented as a range of subsurface pressure values that correspond to a proportional percentage of total object breakage. The range itself is a logit curve, which gives some indication of the degree of fracture within the buried object, mimicking in a sense the breakage dynamic of the object itself.

The usage of the prediction model is:

a) To understand what the breakage thresholds are for each buried artefact type

b) To understand how the breakage thresholds relate to peak subsurface pressures for field operations within this research

c) To relate the breakage of the buried artefact types in this research to other peak subsurface pressures that can come from any outside source, using any chosen proportion of breakage of 100% or lower

This empirically based prediction model provides a reality-based, flexible, and informative method for analysing, predicting, and evaluating situations involving buried artefacts subjected to surface loading.

Mathematical models tend to be idealized, and are not always best for evaluating or predicting real-life situations. The mechanical calculations involve complex factors and elements that many assumptions are necessary to bring the model into a useable form. Buried artefacts are heterogeneous in nature. Regarding ceramic objects, depending on the age of the artefact, the original object would not have been made to any standard other than the potter's own regard of his or her skill. Every ceramic artefact will have been at least slightly different to the next one. The firing process would also have introduced another opportunity for variation, as the firing receptacle could have been anything from a pit in the ground to a more sophisticated kiln-type built construct. There would have been little control of heat intensity, and patterns of air circulation within the 'kiln' could have created hot or cold spots, affecting the integrity of the final product. The aging process will also have degraded the ceramic material to some extent, depending of course on the soil type in which it resided, any past history of surface loading or soil disruption events, as well as the type of temper or clay with which it was made. Thus, it could be expected that every ceramic artefact would present a unique piece; a situation that a mathematical model would be ill-suited to analyze.

The empirical model allows for variability in the soil and artefacts by yielding a probability range relative to any input of a generated subsurface pressure. The breakage threshold ranges is more appropriate for this situation, as the variability in the natural soil-artefact system is too high for a deterministic model to be successful. The more sophisticated and comprehensive approach utilized within this research better evaluates the situation at hand.

There were, of course, some limitations on practical work relating to soil type and moisture status (as discussed in various places). These limitations were dealt with in the following ways.

Instead of trying to investigate subsurface pressures and object breakage in many different types of soil, one soil was chosen. The sandy loam that was used for both the laboratory work and the field work within this research was ideal because it represented a very robust soil type.

The soil type is also a suitable choice for the work relating to artefacts. Sandy loam is representative of a significant portion of cultivated land in England, and would have offered one of the easier cropping opportunities for previous human settlements relying on agriculture. Since this soil is so easy to manage, work, and live on, it would have been a prime soil type for past cultures/societies to utilize for farming or for living upon. This particular soil yields consistent behaviour over various time periods without restructuring (as a clay soil can shrink/swell).

A final note can be made regarding the prediction of the artefact breakage data from the field pressure data. A larger breakage data set would have been nicer, and could have contributed by strengthening the statistical analysis. The limiting factor however, was the large amount of energy and resources necessary within the laboratory studies. This study was able to glean much information from the dataset and correlation method, so although it was not considered a setback for this study, it must be noted.

5.5 Conclusions

Within this chapter, the laboratory breakage thresholds found in Chapter 3 are correlated with the subsurface pressures generated under the field operations from Chapter 4. This correlative prediction model successfully predicts damage to buried artefacts by conventional agriculture.

As the prediction model was created from data generated within this research, it is empirical, and has two limitations. The first relates to soil moisture content. The research was done in the lab at a controlled moisture level, and in the field at 'field' moisture content (not controlled). Because the moisture content was measured and recorded during the fieldwork, it was possible to include this variate within the statistical analysis (in the laboratory work, the moisture content was specified and maintained and thus eliminated variation as an issue). The variation of peak subsurface pressure relative to moisture content within the context of the sandy loam soil utilized for this research was found to be non-significant, and therefore the overall effect from this factor within the results and within the prediction model can be confirmed as minimal.

The second limitation relates to soil type. The effect that any specific soil type has on pressure transfer is more related to the internal and inherent properties involved with the mechanics of the soil. The main focus of this research was less related to the internal soil mechanics behind the pressure transfer and more related to the external factors that caused significant changes relative to buried artefact damage. This discontinuity in the study was acknowledged, and it was decided that only one soil type be utilized, so as to reduce the overall variability from soil type and focus on the external factors that would affect the research outcomes. Since a sandy loam soil was used in both the lab and field, the prediction model should only be applied to sandy loam soils.

The results of the prediction model linking the artefact breakages to the field operations can be concluded as follows.

> The shell tempered pot was found to be the most susceptible to breakage, as it was found to be 100% broken under the Tractor – Trailer operation (rim) and the Shallow Plough operation (body).
>
> The grog tempered pot was the second weakest pot, failing at 100% under the Shallow Plough operation (rim), and the Plough (body).
>
> The flint tempered pot actually never broke all the way, but failed under the Plough to 55% broken (rim) and 20% broken (body).
>
> The quartz tempered pot breakage threshold did not interact at all with the peak subsurface pressures from the field operations, and it was predicted to have remained intact under the entire set of conventional agricultural field operations.
>
> Neither the perpendicular nor the parallel orientated radius bone artefacts showed predicted breakage under any of the field operations; however, other weaker types of bones might be susceptible to damage.

A simple method of evaluating the buried artefact breakage thresholds relative to the field operations was also outlined. This visual analysis of the minimum 100% breakage thresholds relative to the mean peak subsurface pressures of each field operation was presented to offer the reader a different perspective and further insight into the damage potentials of the buried artefacts under agricultural operations. The results did not change the overall breakage correlation analysis done within this chapter. This small exercise and the ensuing discussion about why various field operations generated high or low subsurface pressures relative to each other did offer further knowledge to a farmer or land manager evaluating or planning field operations to avoid artefact damage.

The application of this prediction model within a real-life situation involving the protection of buried artefacts requires a farmer or land manager to choose an acceptable proportion of buried artefact breakage. This is entirely a subjective decision, made relative to the perceived value of the buried artefacts and resources available for artefact damage mitigation.

In order to present an example of the proposed use of the prediction method, the acceptable (or pragmatic) proportion of breakage was set at 50%. Each buried object was evaluated relative to this 50% breakage limit in order to check which field operations could be considered 'safe.'

> The shell tempered pot rim surpassed the 50% limit during the Drill operation (1.03 bar mean peak subsurface pressure), where the predicted breakage was 55%. The shell tempered pot body surpassed the limit during the Tractor-Trailer operation (1.46 bar), where the predicted breakage was 74%.
>
> The grog tempered pot rim surpassed the limit during the Tractor-Trailer operation (1.46 bar), with a predicted breakage of 74%. The grog tempered pot body surpassed the limit during the Shallow Plough operation (1.61 bar), where the predicted breakage was 98%.
>
> The flint tempered pot rim surpassed the limit during the Plough operation (1.61 bar), with a predicted breakage of 55%. The flint tempered pot body never actually surpassed the limit, and the highest predicted breakage was 20% during the Plough operation (1.61 bar).
>
> The quartz tempered pot never sustained any predicted damage, and thus never exceeded 50% predicted breakage.
>
> Both orientations of the radius bones also never sustained any predicted damage, however other types of aged bones could have been susceptible to damage.

Overall, three of the four pot types were predicted to submit to more than 50% breakage under the conventional agricultural field operations within this study. Two of the four pots exhibited 100% destruction under at least one field operation within the study.

The shell pot can be considered to be the weakest pot. There was never any pot or bone damage/breakage predicted under the Roll operation (or the ZigZag or Pigtails accessory operations); this is assumed to have happened because the tractors in these operations were using LGP tyres.

The possible application of this prediction method for use with other ceramic artefact types was also discussed within this chapter. It was however, not recommended that these results be taken and used out of context, especially relative to management of buried artefacts from other parts of the world. The artefact pots were made from specifications relating specifically to UK-type ceramic artefacts, and specifications for manufacture took the methods and tempers from localized cases. It is estimated that some indications of breakage or survival can be gleaned from this research if used relative to other UK ceramic artefact types; however, this must be done at the discretion of the user, as ceramic artefacts are known to be very variable in makeup. If such an indicatory analysis is carried out, it is proposed that a careful, informed review is done of such an auxiliary study by an experienced archaeologist.

The possible application of this prediction method for use with other bone types was discussed, but it is considered impossible to extrapolate the results from the radius bones to other types of aged, human bone. The only way to gain enough such information would be to perform further experimental results that could be comparable to this study. It is acknowledged that the radius bone type was the best choice relative to the experimental demands of this research; however, it was not the most diagnostic type for in-field bone artefact breakage prediction. Nevertheless, the use and study of the radius bone breakage within this research was considered a success, as benchmark values now exist and the evaluation of the bone orientation was also successful (*i.e.*, perpendicular orientated bones are more vulnerable to damage than bones in the parallel orientation).

The use of the prediction model provides a strong empirical approach, available for immediate use by a farmer or land manager. The prediction model can allow insight and inform buried artefact damage mitigation strategies. It is also concluded that within this practical application, it is preferred over the mathematical and more deterministic model type.

From the discussion exploring the usage of the prediction model, it is clear that it the method allows understanding of breakage thresholds per artefact type and how the breakage thresholds relate to peak subsurface pressures from the field operations within this research. The prediction model also allows the breakage of the buried artefacts within this study to be related to other peak subsurface pressures from any outside source. As all situations involving buried artefacts and field management will vary, this method allows the user to choose the proportionate breakage limit most appropriate for the right level of buried artefact protection.

Chapter 6: Overall Discussion

Prior to this research, indirect damage to buried artefacts within agricultural or actively managed lands was noticed but not much understood. This result shed light on how dynamic surface loading – specifically, from agricultural field operations - can harm buried artefacts indirectly, while exploring and quantifying the factors involved. This section discusses the gained knowledge and the development of the techniques and research methods that have contributed to experimental success.

In the laboratory, there were some key innovations that helped shape the course of the experimental trials, particularly as the investigation required subsurface pressure generation and breakage detection in buried brittle objects (without excavation). Pilot studies for the laboratory soil bin work (Appendix E) made good use of a varied range of tyres (drawn over the soil at specific inflations and loads) in order to generate subsurface pressures that ranged from very small to very large in magnitude (applied in multiple passes, with progression from low to high subsurface pressure generation). This approach worked well for generating pressures at 250 mm depth, as their range, and resolution between different magnitudes of subsurface pressures were what was necessary for the trials. Unfortunately, the usage of the multiple tyres caused significant issues within the laboratory environment. Changing between tyres for every run was cumbersome and time consuming. It not only involved the actual tyre change, but also the switching of iron 'tyre rigs' in which the tyres were mounted. This also involved attaching the rig to the soil processor machine that would pull it over the soil. These tyre rigs were large, heavy, and had moving and removable parts. Some had to be loaded with (blocky) weights to achieve the right specification for the pass. One was hydraulically loaded. There was much variation between the tyre setups (for each different tyre, and loading). There was also much opportunity for equipment breakage or malfunction (with so many separate and moving parts). The tyres themselves were very different from each other; some were cross-ply, some radial, some were smooth, some had small tread patterns, and even others had large prominent, stiff lugs. The original aim was to generate subsurface pressure under a simple dynamic surface load, yet the procedures in place were overly complicated.

A simpler approach was needed in order to progress the laboratory work with less opportunity for error, more precision, in less time. Thus, a single tyre was found that was approved within manufacture specifications to safely run at low pressures, light loads, as well as at high pressures, heavy loads. This was not easy, as most tyres seemed to have relatively small ranges of inflation pressures at which they could work under load safely. The tyres which could work at low pressures and low loads did not seem to be able to withstand high inflations and high loads, and vice versa. The tyre that was found to best fit the requirements was a cross-ply agricultural tyre, normally mounted as the back wheel of a combine. It was tested for use within this experiment in some pilot studies first. Inflated to manufacture specifications and loaded with 1 tonne less than maximum allowance for the particular inflation case, the tyre performed very well. The first attempt at matching inflation pressures and loads to generate subsurface pressures under the previously used range of tyres was very successful, and it was obvious that the tyre was a good fit for the laboratory trials.

The final task relative to the tyre choice was to eliminate a final source of variation in subsurface pressure generation. The tyre lugs were not extremely large or prominent, but it was decided to find a way to remove them. This was done in order to minimise any stress concentrations that may have been affecting the magnitudes of subsurface pressure detected by the pressure sensors.

The tyre smoothing procedure was very straightforward once a company was found that had the technical expertise and ability to perform the task. OTR Tyres in Derbyshire was kind enough to help in this aspect, and the tyre was smoothed perfectly, returning ready for use.

The overall result was that the smooth tyre excelled in subsurface pressure generation. The experimental procedure was much improved, as there was no problem changing tyres between runs, and a more efficient, less dangerous, more controlled operation produced very good subsurface generation results.

The problem of detecting breakage in a buried object without excavation had been overcome in previous research (Dain-Owens, 2006). However, the work described here required further innovation. The objects (handmade replicate pot artefacts and aged human bones) used were all porous, and a simple application of lacquer followed by conductive trace was not enough to seal the pot and provide a surface that would allow a continuous circuit to be painted-on. This issue was solved by applying a water-based acrylic solution to the most porous, irregular, or difficult areas of the pots or bones. The acrylic solution was thin enough so that it created a smooth surface without affecting the strength of the material. The conductive trace was applied after it had dried. The use of this water-based acrylic solution to create a smooth surface on the artefact was essential in allowing a continuous circuit without further issue.

A second achievement relative to the method of subsurface breakage detection was the digital recording of the circuit traces. This allowed the pot traces to be recorded and logged into a digital file. The recordings became very valuable during post-processing of the laboratory trials, as it became possible to visually inspect the traces. The sensitivity of the circuit traces in response to object cracking and breakage was also possible to be seen in the recorded data. This was important, as it allowed breakage detection in each object to be evaluated more holistically, on a larger time scale. As the circuit relative resistance values were linked to the buried object, it was possible to compare runs within trials, as the resistance values at the start and end of each run were simply a continuation of the values recorded in the previous run. Fluctuations, jumps, and various events within the electrical signal were recorded in this way, and the breakage threshold results yielded much more information about what was happening to the pots while buried and subjected to loading.

Once the recording and data logging of the circuit traces was fully developed, it was time to correlate the breakage to the peak subsurface pressures. The correlation of the object breakage and peak subsurface pressures under which the objects broke was straightforward. However, one aspect of the subsurface pressure data facilitated this correlation.

It related to the magnitudes of the generated pressures. There were six runs per trial, with the lowest generation peak subsurface pressure in run #1 (0.8 bar) and the highest in run #6 (3.8

bar). The mean difference between the peak subsurface pressures between each of the runs was 0.65 bar. The analysis of these pressures showed that the least significant difference (LSD) between runs #1 through #6 was 0.13 bar. This, being less than the mean difference between each peak pressure, meant that each peak subsurface pressure could be treated individually, and with confidence. It also meant that the breakages could be correlated with the peak subsurface pressures individually, thus allowing better accuracy in indentifying the breakage threshold range of each buried artefact.

The identification of the breakage threshold range as opposed to a single line threshold value was important. The breakage threshold range responded to a logistic curve that was calculated during the statistical analysis correlating the breakage of the buried pots and bones to the peak subsurface pressures. The range was logistic, with a logistic curve displaying percentage of artefact failure per peak subsurface pressure. A pressure threshold breakage range was identified for each of the two failure zones within each artefact type, for all artefact types.

The use of the logistic curve to correlate the artefact breakage data to the subsurface pressures to create the threshold range, modelled with a logistic curve, mimics in a sense, the breakage dynamic of the brittle artefact. An unbroken, brittle object will generally start to crack under a given applied pressure. Being brittle, the object will not bend before the cracking point. And once the cracking starts, the propagation of cracks will quickly spread to other areas of the object even with just slightly more pressure application. The brittle artefact does not shatter in one instant, however, there is a slim range of pressure application during which the artefact will crack and become shattered. The logistical curve is good at replicating the speed and character of this breaking dynamic; hence the breakage threshold range provided much information in addition to breakage points.

The breakage to pressure correlation is a unique, innovative, and useful application of data analysis that is well-suited for the situation and yields much information about properties of the artefacts' breakage dynamic and the subsurface pressures at which they fail. Since the logistic curve mimics the breakage dynamic of the pots, the threshold range presented from the data analysis allows insight into the particular breakage character of each artefact type. Using the breakage data from the laboratory trials, it shows accurately the peak subsurface pressures at which each object will begin to crack, when say, over 50% of the object will have been broken, and when the entire object will have broken. This information becomes even more useful when the breakage threshold ranges are compared to the peak subsurface pressures recorded under the field operations included in this research.

Once the breakage threshold ranges were defined, it was possible to quantify them relative to the subsurface pressures generated in the field by conventional agricultural operations. This particular correlation involved utilization of the breakage threshold analysis as a prediction model to indicate whether or not the artefact type in question would be broken under any of the field operations, thus satisfying one of the main aims of this research.

The prediction model was a transformation of the survival equation built from the breakage data in the laboratory trials. This empirical type of prediction function was chosen in order to better respond to 'real-life' scenarios. It was observed that variability in the surface loading, soil profile, and artefact material was higher than a deterministic model could handle successfully. It was recognized that there were of course, limitations within practical work, such as challenges addressing an effect of soil type and moisture status on buried artefact breakage from surface loading. Variation of moisture content was addressed by this study, however soil type was not, as the scope of the work was considered out of range of this research.

For the prediction model, the input value (x) was a peak subsurface pressure value, and the output value was the 0-100% proportion of the artefact type that would be broken after being subjected to the peak subsurface pressure input. Because the prediction model was created with empirical data from the laboratory trials, and because it also uses input data relative to real subsurface pressures generated under field operations, variability within the empirical process is introduced, and the final prediction inherently retains this. The equation was calculated for each field operation's mean peak subsurface pressure generation, and was specific to individual artefact types. The resulting table indicated how much of each artefact would be broken if buried under the wheel/track path of any of the field operations used in the field experiments.

The correlation of the artefact breakages and the field operation subsurface pressure generation allowed further insight into the potential damages to buried artefacts, as it yielded much more information than simply whether or not the artefact had broken. The prediction model can help a user to evaluate whether specific artefact types could be 'safe' relative to certain field operations. The prediction model can also be used in other contexts apart from this research, giving warning of dangerous field operations or indicating whether buried artefacts previously subjected to surface loading might have been harmed. Any peak subsurface pressure can be used as an input in the equation, so whether the vehicle in question is a small quad bike or a large truck, as long as there is data (or an estimation) of a peak subsurface pressure value, the prediction model will work, identifying if there is danger for artefact damage from the vehicle or field operation.

This work can serve as a reference study on buried artefact damage in relation to actively managed lands. The breakage thresholds that have been established for the pot types and bone types in this study, as well as the prediction function and its abilities, will provide cornerstone knowledge and aid in future research within this subject. The quantification of the dynamics within the breakage of buried artefacts subjected to surface loading is very useful to anyone interested in mitigating in-situ buried artefact damage.

The artefact breakage threshold results are informative, especially when correlated to field operations. Of course, these correlations can only be applied to situations specific artefact types. The subsurface pressures collected under field operations however, can be applied within any project working in a similar sandy loam soil type, thus informing other situations and research. This is important because the field study has succeeded in presenting a comprehensive collection of subsurface pressures recorded under a complete set of contemporary and conventional agricultural field operations. While subsurface pressures under field operations have been measured within research for various purposes for decades, this study presents robust subsurface pressures measured under a very complete set of modern agricultural operations. These operations include agriculture vehicles for a cropping cycle, as well as readings from all the operations as they operate in soil that has been treated with different cultivation regimes (plough, shallow plough, non-inversion, and zero till). The operations used are all conventional and modern so that the data recorded under them can be trusted in comparison with other similar vehicles and implements within the agriculture and field management sector, as much current field machinery has comparable specifications. Additionally, the study was completed entirely within a sandy loam soil type, allowing the pressure generation abilities of various field operations to be compared to each other. All this should place it respectably amongst other landmark soil-pressure studies in the literature.

An additional point of discussion related to subsurface pressure generation can be made relative to cultivation scheme. As noted in Chapter 4, the mean of all operations' peak subsurface pressures generated within the differently cultivated plots showed significant differences between cultivation techniques. The zero-till cultivation regime yielded subsurface pressures significantly lower than what was generated in both the shallow inversion and inversion plots. The non-inversion plot yielded subsurface pressures higher than zero till, but still significantly lower than in the inversion plot. The motivation for using different cultivation regimes will always be relative to the farmer or land manager and their evaluation of their soil's needs and status. However, a general method to keep peak subsurface pressure generation lower could be to avoid inversion cultivation techniques when feasible, and to use a zero till policy if it is considered a viable option.

The investigations of this research into the breakage of subsurface artefacts and their breakage thresholds, subsurface pressures under field operations, as well as the correlation of breakage to field operations are valuable to soil and land management, whether relative artefact and historical resource management or solely in relation to best management practice principles for soil and land. The principles of good buried artefact management and good land management come hand in hand with each other. What is good for protecting buried artefacts is inherently good for maintaining a sustainable soil system, and vice versa.

An approach to successful artefact damage mitigation can be simple. A first step would be information gathering on the artefacts that are known or suspected to be within the soil. It is important to be informed about what materials are buried in the field soil, their value, their state of degradation, and if possible, their location and depth. This may not necessitate a full excavation, as it would be likely that a desktop study researching historic documents, probing people's common knowledge, augmented with an appropriate geophysics study could inform this stage. If necessary, some small test excavations could be arranged if the buried artefacts are considered particularly valuable or if not enough information is found elsewhere.

Once the artefact type and associated information is researched, an assessment can be made to see if the results and prediction model from this research can help to advise a protection plan. If the artefact type is ceramic, it could be possible to compare it to and evaluate it with the prediction model within this research. If the ceramic artefact type is known, then it can easily be matched to whichever pot within this study it is most similar in material composition. If the pot type is the same as one of pot types tested within this study, then it is an easy match. If the ceramic type is unknown, then it would be best to recommend maximum artefact protection and it can be matched with the weakest pot-type, which in this study represents a worst-case scenario.

For the pots similar to the quartz or flint tempered ceramic artefact types, most normal conventional field operations should not harm them. This statement assumes that the field operations are representative of average vehicles and machines, and are not unusually large or heavy relative to contemporary standards. Any tractor and trailer combination would need to be monitored however, to ensure that the trailer is not overloaded and remains below 8 tonnes (the maximum load within this study).

For pots similar to shell or grog tempered ceramic artefact types (or if the pot type is unknown), they could be in considerable danger of being damaged by normal conventional field operations. Any inversion tillage operation, whether shallow or deep, should be avoided. If it is possible relative to the soil system, a zero till cultivation regime would help keep peak subsurface pressure generation lower. Passage of the tractor and trailer combination should also be strictly avoided, no matter what the load. Low ground pressure (LGP) tyres could be used on all sizes of tractors in order to help reduce surface loading if it is necessary to drive over the area where the artefacts are known to be. LGP tyres are not guaranteed to eliminate the danger of ground pressures high enough to damage buried ceramics, and the soil status and potential machinery differences must also be considered; however, they were shown within this study to greatly reduce the subsurface pressure generation under field vehicles. The soil status should also be monitored to ensure that it is not too wet, as wheel sinkage would further threaten buried artefacts. Knowing the locations of these weaker ceramic artefacts would increase their chances of survival, as it would then be possible to allow the field operations driver to avoid driving over them and threatening them with damage.

If the artefact type is bone, this study may not provide a complete set of recommendations for preserving them. Until more is known about buried aged bone breakage, exact recommendations cannot be made. This is because the results of this study represent a stronger bone type, and it is expected that some other bone types are weaker (or stronger) than the radius. The breakage threshold range is not known for most types of human bones. However, some suggestions for a sensible protection strategy can be made, based on this study. If it is possible to avoid passing over the bones with wheels/tracks, it would be allow the bones further protection. Also strong efforts should be made to reduce surface loading of the soil. This would involve using LGP tyres, keeping trailer loads light, and using non-inversion or zero till cultivation techniques.

General recommendations can also be made relating to the size of the artefact. If the artefact is bigger, it will generally break under less subsurface pressure than if it was smaller, no matter what material. If the material is known, and if it can be compared at all to the artefact types used in this research a more informed evaluation can be made relative to whether it will or will not be damaged under specific field operations. If the artefact material is unknown, specific recommendations cannot be made, but the general principles of keeping large surface loads away from buried artefacts will always apply.

One last note should be made relating to the depth of an artefact. As the magnitude of pressure transferred through the soil under a surface load has been proven to degrade with depth, if the object is buried deeper than 1 m in the soil profile, and if the soil is subjected to normal field operations, the artefact should be safe from damage. If the artefact is located within the uppermost 250 mm of the soil profile, it is at risk from direct damage from ploughs, tines, or other soil-engaging tillage implements, as well as at a heightened risk of indirect damage (both are not covered by this research). If the artefact is located around 250 mm depth, the risk of damage is equal to that presented in this study, as all laboratory and field trials tested objects buried at 250 mm depth. If the artefact is located deeper than 250 mm depth but shallower than 1 m depth, then the risk for damage will probably be relative to the depth, The shallower the object is buried, the higher the risk will be for damage.

As previously mentioned, these recommendations will not only protect the buried artefacts but also positively impact the sustainability of any soil system. While this aspect of soil management was not the main focus of this research, it is valuable to consider the overall benefits and long-term maintenance of soil systems.

A sustainable soil system is generally comprised of a soil that is well-structured, without compaction – at shallow or deep depths, has a top layer that will receive moisture and allow infiltration to deeper layers of the soil profile, has healthy and beneficial macro- and micro-biological communities, and has a soil chemistry that is appropriate for the crop growing in it, as well as the surrounding natural environment. Such a soil system is able to provide a balanced growing medium for plants and habitat for living organisms that does not need extreme efforts to maintain it or prevent degradation. By being well structured and maintaining above and below ground biomass and macro and micro biology, it becomes generally more resilient, with the ability to absorb more pressure within the upper layers (horizons) of the soil profile, thus preventing deeper transfer of peak subsurface pressures.

A sustainable soil system will thus benefit from monitoring the soil status prior and during fieldwork. If the soil is too wet or has been overworked, the sustainable state of the soil will become degraded. Knowing the soil type and its variation across the land will help in evaluating soil status, enabling the land manager to specify timing of fieldwork and/or different treatments in different fields, or avoiding the usage of heavier vehicle in areas that are perennially wet for example. This will enable the soil to retain its structure, and will also limit wheel sinkage, which damages soil structure and creates deeper compaction causing impervious layers of soil. A reduction of overall surface loading of the soil will help the soil remain resilient and viable for maximum plant growth and produce production. Less compaction will allow root zones to expand without limitation, and will allow correct infiltration and drainage within the soil system, avoiding perched water tables and anaerobic soil conditions. Healthy soil will also be less susceptible to erosion and the levels of finer particles and organic material within the soil can be maintained, aiding in plant growth. Reduction of overall surface loading can be achieved by using LGP tyres on tractors and field vehicles. Monitoring and limiting loads on tractor trailer combinations will also help. The avoidance of inversion tillage will also help lower overall peak subsurface pressures, as it will enable the soil to maintain its structure, healthy macro and micro biology levels, and will reduce erosion. If a zero till cultivation system is possible, it could be of further use in achieving overall reduced peak subsurface pressures.

The results of this research not only benefit researchers, but also soil and land managers, while supporting efforts to promote sustainable soil systems. Evaluating buried artefacts and their susceptibility to damage is possible, and simple measures can be taken to prevent or minimise damage. The prediction model is a useful tool, whether utilized to predict breakage for specific artefact types, or as an indicator to aid understanding of the breakage thresholds and dynamics of artefact types that might be under threat within intensely managed lands. The understanding of the processes and effects of peak subsurface pressure thresholds is essential to minimise artefact damage, and this research provides a strong base for such an approach.

Chapter 7: Conclusions & Recommendations

7.1 Conclusions

The aim of this work was to investigate the influence of surface loading from conventional field operations on buried artefact damage.

The four objectives were as follows:

1. To investigate the influence of surface loading and resulting breakage relating to the material strengths of buried objects - terracotta, ceramic (unglazed), and aged bone.
2. To assess the magnitudes of peak subsurface pressures transferred through soil under the dynamic surface loading from tyres and other field operations.
3. To develop and test a model for predicting the effects of subsurface pressure application on buried objects from surface loads
4. To explore ways of identifying the potential for damage to buried artefacts under agricultural and other field operations

The aim and objectives have all been investigated, and the following conclusions can be drawn from the research presented within this thesis:

I. This study has developed a functional and predictive empirical relationship between damage to pot and aged bone artefacts from subsurface soil pressures generated by surface traffic.

II. This relationship shows that the different pot and bone types investigated within this research break at different subsurface pressures.

   a. The four pot types for which breakage thresholds were found, listed in ascending order of strength to resist damage (with breakage pressure threshold value) when buried in a horizontal position in the soil are: shell tempered (1.3 bar), grog tempered (1.6 bar), flint tempered (3.1 bar), and sand tempered (3.6 bar).

   b. Aged human radius bones were tested, with a single bone type buried in two different orientations relative to surface loading path. This resulted in an evaluation of resistive strength to damage relative to bone orientation.

      i. Breakage did not occur in the parallel-orientated radius bone, proving this orientation to be stronger than the perpendicular orientation.

      ii. The lowest subsurface pressure found to cause damage to the perpendicularly orientated radius bone was found to be 2.8 bar.

III. A complete dataset has been compiled, consisting of peak subsurface pressures recorded under a year's range of field operations within a sandy loam soil at field-working moisture content. The effect of different cultivation methods on the generation of subsurface pressures has also been evaluated. While the purpose of collecting this subsurface pressure data was to support understanding of artefact damage caused by field operations, the results are relevant to a larger range of interests. For example, an additional area of application is in understanding the effects of field operations on soil compaction processes.

   a. The primary field operations, presented in ascending order relative to peak magnitude of subsurface pressure per specific operation, are: roll (0.68 bar), drill (1.03 bar), simba solo (1.21 bar), spray 1 (1.27 bar), harvester (1.30 bar), spray 2 (1.31 bar), tractor / trailer (1.46 bar), shallow plough (1.61 bar), plough (2.04 bar). Relationships between vehicle specification and subsurface pressure generation potential have been described, relating to the vehicle mass, tyre/track physical properties, and tyre inflation pressure.

   b. The effect of cultivation method on overall magnitude of subsurface pressure can now be defined. Overall mean subsurface pressure generation is lower within a zero-till cultivation regime (1.08 bar), higher in a non-inversion cultivation regime (1.13 bar), even higher within a shallow inversion regime (1.22 bar), and highest within a conventional inversion scheme (1.30 bar).

IV. The breakage thresholds specific to each artefact type have been related to the in-field subsurface soil pressures. A correlation of breakage to the subsurface pressures under each operation yields a prediction of percentage of artefact-type breakage. From this correlation, relationships are observed between vehicle specification, subsurface pressure generation, and consequential artefact breakage.

   a. The potential artefact damage relative to in-field operations can define a measure of extent of harm in damage to artefacts. This analysis was done relative to a 50% proposed acceptable proportion of artefact damage, where over 50% artefact breakage is considered 'unacceptable' and below 50% is considered 'acceptable,' with an evaluation of each artefact type for potential damage.

      i. The shell tempered pot is most susceptible to damage, as the 50% breakage level is exceeded under all field operations including any tillage operation except for the rolling operation.

         1. The prediction equation for the shell tempered pot type rim is:

$$P = (100 * \exp(17.80 * \chi - 18.20)) / (1 + \exp(17.80 * \chi - 18.20))$$

      ii. The grog tempered pot is less vulnerable to damage. The 50% breakage level is exceeded under any shallow or conventional depth ploughing operation and under a tractor-trailer operation. The other field operations were not shown to pose a threat, but if vehicles/operations differ from that in this research, re-evaluation could be necessary.

1. The prediction equation for the grog tempered pot type rim is:

$$P = (100 * \exp(40.90 * \chi - 58.82)) / (1 + \exp(40.90 * \chi - 58.82))$$

iii. The flint tempered pot was predicted to sustain the most damage under the conventional-depth ploughing operation, although it was not predicted to fail completely.

1. The prediction equation for the flint tempered pot type rim is:

$$P = (100 * \exp(4.60 * \chi - 9.15)) / (1 + \exp(4.60 * \chi - 9.15))$$

iv. The quartz tempered pot was predicted to survive intact under all field operations within this study, and the extent of likely damage could be considered 'acceptable' under normal field conditions and operations.

1. The prediction equation for the quartz tempered pot type rim is:

$$P = (100 * \exp(21.80 * \chi - 72.20)) / (1 + \exp(21.80 * \chi - 72.20))$$

b. It is evident that agricultural practices, choice of track or tyre type, and inflation pressures must be carefully managed if the intention is to protect or mitigate damage to buried archaeological artefacts.

i. The three most important factors affecting ground pressure propagation have been seen to be the overall and/or proportional mass of the operation, tyre type or use of a track, and tyre inflation pressure.

ii. With more mass versus less mass, more pressure will be generated subsurface. With a small-diameter, thin-section, non-flexible, or sharper-profile tyre, versus a large-diameter, wide-section, flexible, smooth-profile tyre or the use of a track system, more pressure will be generated subsurface. With a higher specification for tyre inflation pressure versus less inflation pressure, more pressure will be generated subsurface. These three factors can be used in various combinations to mitigate the effects of each other.

iii. For example, if an operation has a large mass, but is able to utilize a large-diameter, wide-section, flexible, smooth-profile tyre inflated to a lower inflation pressure, the subsurface pressure generation can be significantly reduced. If an operation has less mass, but is mounted with small-diameter, thin-section, non-flexible, or sharper-profile tyres that are inflated to a higher inflation pressure, the subsurface pressure generation will be made substantially higher.

V. A contribution has been made to the development of 'best management practices' and to the specification and use of field operations relative to intended mitigation of buried artefact damage.

a. The development of the empirical prediction model provides a tool enabling any user to manage risk of in-field artefact damage by designating an 'acceptable' allowance of percentage artefact damage relative to a specific artefact type and field operation. A limiting target for subsurface pressure generation subjectively specified and relating to the context of each situation can be set and field operations specified and managed to prevent subsurface pressure generation exceeding these limits.

b. Subsurface pressures can be managed relative to designated limitations in a number of ways, relative to vehicle specifications. One example of a modification choice that would help reduce subsurface pressure generation would be to mount low ground pressure tyres (large-diameter, wide-section, flexible, smooth-profile) on any field operation that normally utilizes small-diameter, thin-section, non-flexible, or sharper-profile tyres. In this study, this modification would be especially useful if applied to the spraying operation. This operation is already light, and a simple tyre-choice operation would lower subsurface pressure magnitudes to more acceptable levels.

VI. Additionally, this research provides novel contribution of innovative experimental methodological techniques.

a. The concept of a laboratory system using the smooth tyre to generate subsurface pressures whilst burying pressure transducers alongside artefacts for investigating buried object breakage proved to be a successful solution for the detection of buried object breakage thresholds.

b. A method for detecting instant-of-breakage of buried objects has been successfully adapted and applied to handmade pots and aged bone.

c. The innovative application of the survival-statistics-type analysis that utilized a binomial regression in order to calculate the threshold range delivered appropriate and informative results, providing successful analysis of a limited number of data artefact subjects.

d. The imposed accelerated-time framework built into the field methodology allowed comprehensive (both in terms of equipment types included and amount of data collected) generation of subsurface pressure data.

7.2 Recommendations

The results and conclusions presented within this research programme form a foundation for further development of the theory and processural relationships between the areas of archaeology and agriculture soil dynamics. This practical work provides a base from which future theoretical or practical work can refer to, while at the same time identifying opportunities for further research.

The following areas of opportunity have been identified that could provide much information on a multidisciplinary level.

1) The investigation into the breakage of buried aged human bone artefacts from surface traffic within this research provides useful knowledge about buried aged bone breakage from agricultural operations. However, surrounding ethical and practical concerns became limiting factors, as only one bone type was employed. The subject is pertinent to the disciplines of archaeology, paleoarchaeology, biomechanics, and (forensic) taphonomy, and further research would be valuable.

    i) A study should focus on gaining a wider understanding of the type, extent, and pressure magnitudes associated with the critical breaking thresholds of multiple types of aged human bone buried within the soil matrix. Ideally, multiple, whole, aged-bone human skeletons could be utilized for investigation. As this is not ethically sound, nor practically viable, an innovative solution would need to be developed.

2) Another proposal for future research relates to the detection of buried object breakage. The efforts within this research were successful and reliable. However, the methodology could be refined to further lessen data variation, allowing for automated non-subjective identification of breakage. In any experimental project, efficient and well-developed laboratory solutions facilitate the exploration of theoretical issues.

    i) Further development of buried object breakage detection instrumentation system should aim for less variable breakage detection.

        (a) Such instrumentation developments would need to be adapted to match the specific material of different types of buried objects. The material of the buried object itself in any future study could also be under scrutiny, as it was seen that the amount of heterogeneity in the handmade ceramic pots in this study affected their breakage properties.

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Appendices

Appendix A: Soil texture classification

Cranfield Study Identifier: NR-SAS/037/09 – Laboratory Manager: Mr Richard P. Andrews

A.1 Analytical Methods

1. Before commencement of this contract the samples were refrigerated at approximately 4°C.
2. NR-SAS / SOP 1 (Sample receipt, storage, preparation and disposal). The sample material was received, stored prior and during analysis in a manner that best suited the analytical requirements [BS 7755 Section 2.6 (1994) Guidance on the collection, handling and storage of soil for the assessment of aerobic microbial processes in soil, BS ISO 11464:2006 Pre-treatment of samples for physico-chemical studies and Method 1 of the MAFF Reference Book RB427 (1986) Analysis of Agricultural Materials].
3. NR-SAS / SOP 5 (Particle size distribution). This was determined by the method of sieving and sedimentation on the mineral fraction of a study material [BS 7755: Section 5.4 (1998)]. The texture classes are obtained from BS 3882 (2007) Specification for topsoil and requirements for use.

A.2 Analytical Results

Table A.1: Analytical results of soil texture classification for laboratory soil bin and field plots

source:	soil bin	zero till	inversion	non inversion	shallow inversion	field control
% of: 0.6mm - 2mm	6.95	9.24	6.34	5.03	4.48	7.29
% of: 0.212mm – 0.6mm	33.99	42.87	39.35	42.17	41.43	45.47
% of: 0.063mm – 0.212mm	25.74	16.51	21.80	20.75	21.60	17.71
% of: 0.002mm – 0.063mm	18.92	18.51	18.63	19.23	18.37	17.28
% of: < 0.002mm	14.42	12.88	13.89	12.85	14.12	12.27
Texture class according to BS 3882 (2007)	sandy loam	sandy loam	sandy loam	sandy loam	sandy loam	sandy loam

Particle size distribution is reported on a peroxidised, oven-dry basis

Appendix B: Sensor Specifications from Manufacturer

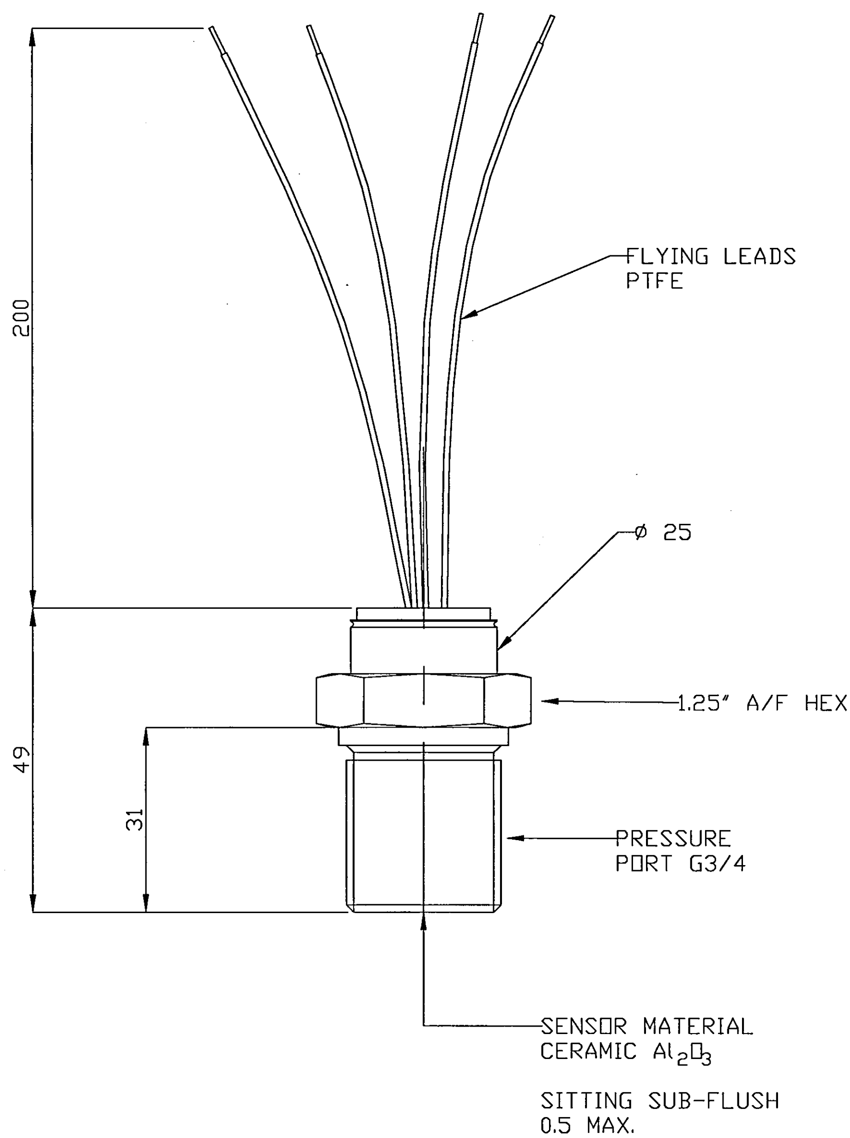

Figure B.1: Scale engineering drawing for ceramic sensors.

Manufactured by Roxspur specifically for Cranfield University as a modified version of model # M6420-92. Manufactured to industry standards, they can sense applied pressures up to 10 bar (1.0 bar = 14.5 psi = 100.0 kPa). The minimum sensitivity, or electrical resolution, of the sensors was 0.0007 bar. After considering the steady state noise in the data recording, a realistic minimum sensitivity was found to be ~ 0.02 bar.

Appendix C: Data logging specifications, Instrument settings

A FYLDE data-logger was used to record data from pressure transducers. The FYLDE devices used the following data amplification settings for recording signal from the cylindrical strain gauge pressure sensors:

Gain = 1x * 100 = 100
Bridge voltage = 10V

Simple USB-based 'Personal Measurement Devices' (PMDs) were used for recording the relative residual voltage across conductive traces on the buried bone and ceramic objects, where no signal modification or amplification was necessary. The PMDs were used in the 8 single-ended analog input mode, at 12-bit resolution.

Data was logged at a rate of 100 hertz in the laboratory and 500 hertz in the field.

Appendix D: Sensor calibration

D.1 Lucas pressure test pump calibration (pressure gauge to true pressure)

Date – March 18, 2003 (Kim Blackburn) using a Budenburg Deadweight Tester

0-160 psi Lucas pressure gauge

Applied Pressure	Lucas gauge indication
0	0
20	19
40	41
60	60
80	80
100	101
120	121
140	142

Correlation calculation, using full range of recorded values

Slope: 0.9858 Intercept: 0.5033

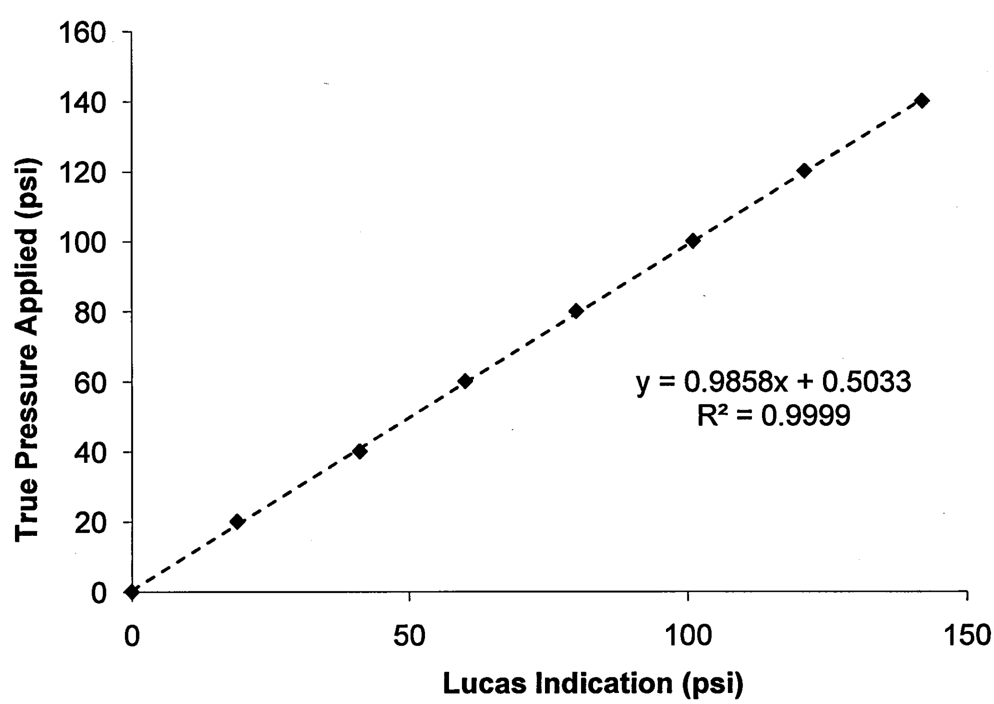

Figure D.1: Lucas pressure gauge (0-160 psi) calibration to true pressure

D.2 Lucas pressure test pump calibration (pressure gauge to true pressure)

Date – March 18, 2003 (Kim Blackburn) using a Budenburg Deadweight Tester

0-30 psi Lucas pressure gauge

Applied Pressure	Lucas gauge indication
0	0.0
10	11.0
15	16.0
20	20.8
25	25.7

Correlation calculation, using full range of recorded values

Slope: 1.0122 Intercept: 1.0824

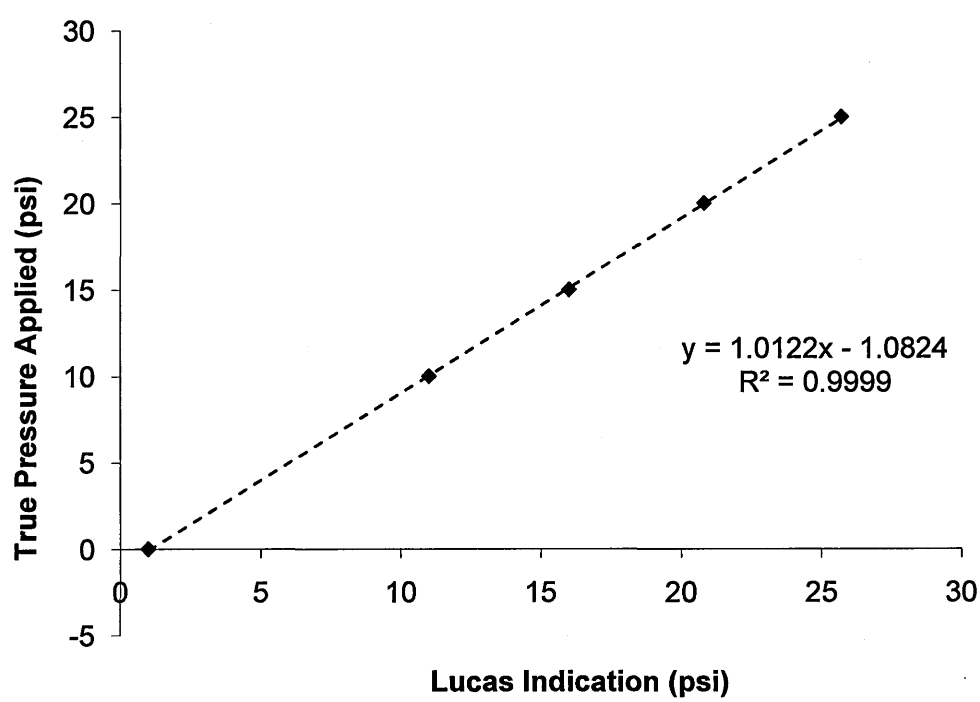

Figure D.2: Lucas pressure gauge (0-30 psi) calibration to true pressure

D.3 Pressure transducer calibration (for sensors used in both field and laboratory)

The calibration of the pressure sensors used within this research (see Appendix A for sensor specification) was done with air pressure system. The Lucas pressure gauges (either 0-30 psi range or 1-160 psi range) were used to sense the applied air pressure, and a FYLDE data logger was connected to a computer to create a reliable data collection system. The following table shows the calibration data, the regression values for the applied pressure to the sensor outputs, and the resulting calibration coefficients that were used (10 V was the excitation voltage utilized for the pressure sensors throughout the experiments within this research).

Table D.3: Calibration data and calculations for the pressure sensors within this research (field and laboratory).

sensor usage	logger channel	sensor ID	sensor output per excitation (mv/V)	sensor output (mV)	true pressure (bar)	slope of regression	R^2 value	calibration coefficient for 10V excitation
inversion	1	1	0.497497557	4.974975574	-0.073632089	2.304376424	0.9968	0.230437642
			0.679747164	6.797471636	0.442610848			
			0.907858268	9.07858268	0.958853786			
			1.141353114	11.41353114	1.454851903			
			1.251221312	12.51221312	1.687667346			
inversion	2	2	0.416417494	4.164174939	-0.073632089	2.356173121	0.9984	0.235617312
			0.581070845	5.810708448	0.391998796			
			0.816489256	8.164892557	0.938608965			
			1.035561934	10.35561934	1.424484671			
			1.265199538	12.65199538	1.95085002			
inversion & lab	3 (field) / varied (lab)	3	0.431151332	4.311513315	-0.073632089	2.27057801	0.9979	0.227057801
			0.616129804	6.161298039	0.432488438			
			0.836589061	8.365890608	0.928486555			
			1.085751874	10.85751874	1.454851903			
			1.310596396	13.10596396	1.95085002			
zero till	12	5	0.52678785	5.267878498	0.027592016	2.211364528	1.0000	0.221136453
			0.715581335	7.155813351	0.452733259			
			0.929259104	9.292591042	0.928486555			
			1.172835815	11.72835815	1.464974314			
			1.396479898	13.96479898	1.95085002			
zero till	11	6	0.503089496	5.030894957	0.027592016	2.215438359	0.9998	0.221543836
			0.68686466	6.868646602	0.432488438			
			0.905321906	9.053219055	0.928486555			
			1.134343233	11.34343233	1.444729493			
			1.375523221	13.75523221	1.95085002			
shallow inversion	6	7	0.632548129	6.325481287	0.027592016	2.215484641	0.9999	0.221548464
			0.811909602	8.119096018	0.432488438			
			1.037307186	10.37307186	0.938608965			
			1.276455817	12.76455817	1.444729493			
			1.496472558	14.96472558	1.95085002			
zero till	10	8	0.521773792	5.217737917	0.027592016	2.22444271	0.9999	0.222444271
			0.709715994	7.09715994	0.452733259			
			0.923966119	9.239661186	0.938608965			
			1.163328351	11.63328351	1.464974314			
			1.386746388	13.86746388	1.95085002			
non-inversion	7	9	0.378467793	3.784677934	0.027592016	2.224143132	1.0000	0.222414313
			0.559231505	5.592315051	0.432488438			
			0.783043686	7.830436862	0.938608965			
			1.024394133	10.24394133	1.464974314			
			1.251594388	12.51594388	1.971094841			

Table continues on next page.

shallow inversion	5	10	0.582760339	5.827603388	0.027592016	2.179934897	0.9999	0.21799349
			0.760936721	7.609367215	0.432488438			
			1.000298954	10.00298954	0.948731376			
			1.23428002	12.3428002	1.444729493			
			1.460089686	14.60089686	1.95085002			
non-inversion	8	11	0.545324085	5.453240851	0.027592016	2.261172811	1.0000	0.226117281
			0.718528263	7.185282628	0.422366027			
			0.942358287	9.423582875	0.928486555			
			1.167384198	11.67384198	1.434607082			
			1.39520051	13.9520051	1.95085002			
shallow inversion	4	12	0.639972894	6.399728943	0.027592016	2.255480012	1.0000	0.225548001
			0.809781959	8.097819588	0.422366027			
			1.041176705	10.41176705	0.938608965			
			1.267987404	12.67987404	1.444729493			
			1.485430701	14.85430701	1.940727609			
non-inversion	9	14	0.432876276	4.328762755	0.027592016	2.257675296	1.0000	0.22576753
			0.616629464	6.166294643	0.452733259			
			0.834263393	8.342633929	0.938608965			
			1.061463648	10.61463648	1.454851903			
			1.284080038	12.84080038	1.95085002			
lab	varied	13	0.319076849	3.190768495	0.027592016	2.180804768	0.9999	0.218080477
			0.498844069	4.988440689	0.432488438			
			0.727638712	7.276387117	0.938608965			
			0.967992666	9.679926658	1.444729493			
			1.197983099	11.97983099	1.95085002			
lab	varied	18	0.580192534	5.801925338	0.027592016	2.173347981	0.9999	0.217334798
			0.773722919	7.737229187	0.452733259			
			1.005321587	10.05321587	0.958853786			
			1.22376577	12.2376577	1.444729493			
			1.458752716	14.58752716	1.930605199			
lab	varied	Z	6.7139E-06	0.000067139	-0.073632089	2.299888717	0.9999	0.229988872
			0.448045969	4.48045969	0.912136741			
			0.859882832	8.598828316	1.897905571			
			1.28845768	12.8845768	2.883674401			
			1.729665566	17.29665566	3.869443232			
			2.16287384	21.6287384	4.855212062			
			2.584069061	25.84069061	5.840980892			
			3.014613915	30.14613915	6.826749723			
			2.571547699	25.71547699	5.840980892			
			2.135837936	21.35837936	4.855212062			
			1.711161804	17.11161804	3.869443232			
			1.276370907	12.76370907	2.883674401			
			0.862980366	8.629803658	1.897905571			
			0.457136822	4.571368217	0.912136741			
			0.001136169	0.011361694	-0.073632089			

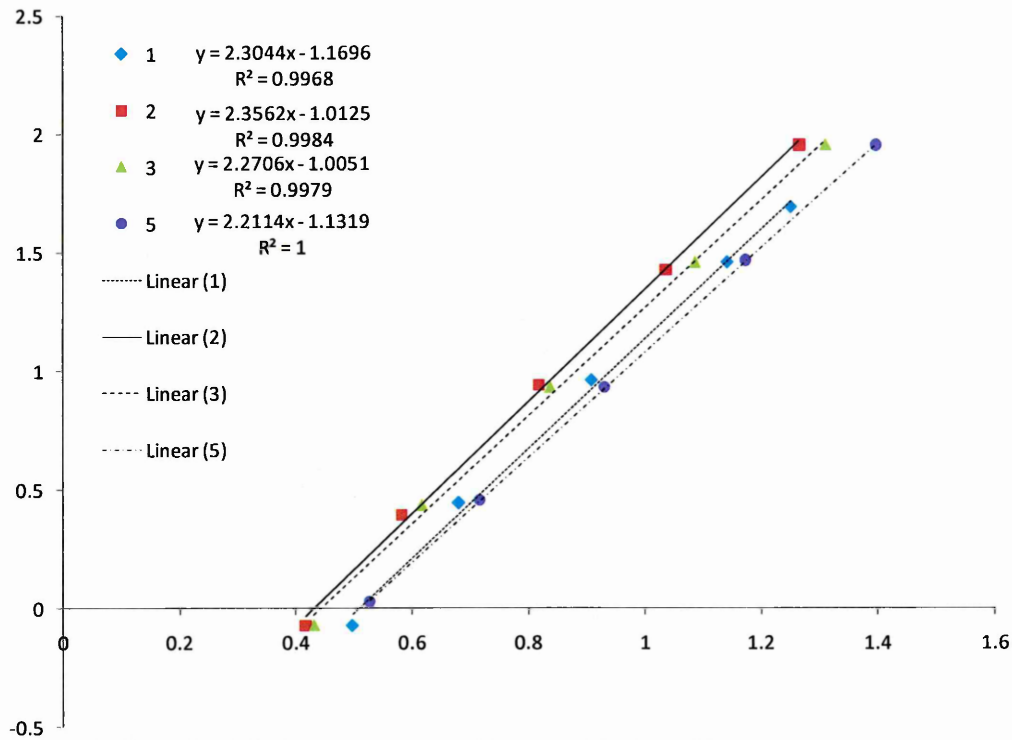

Figure D.3: Calibration data, regression line and regression equation for sensors with ID numbers 1, 2, 3, and 5 used within this research.

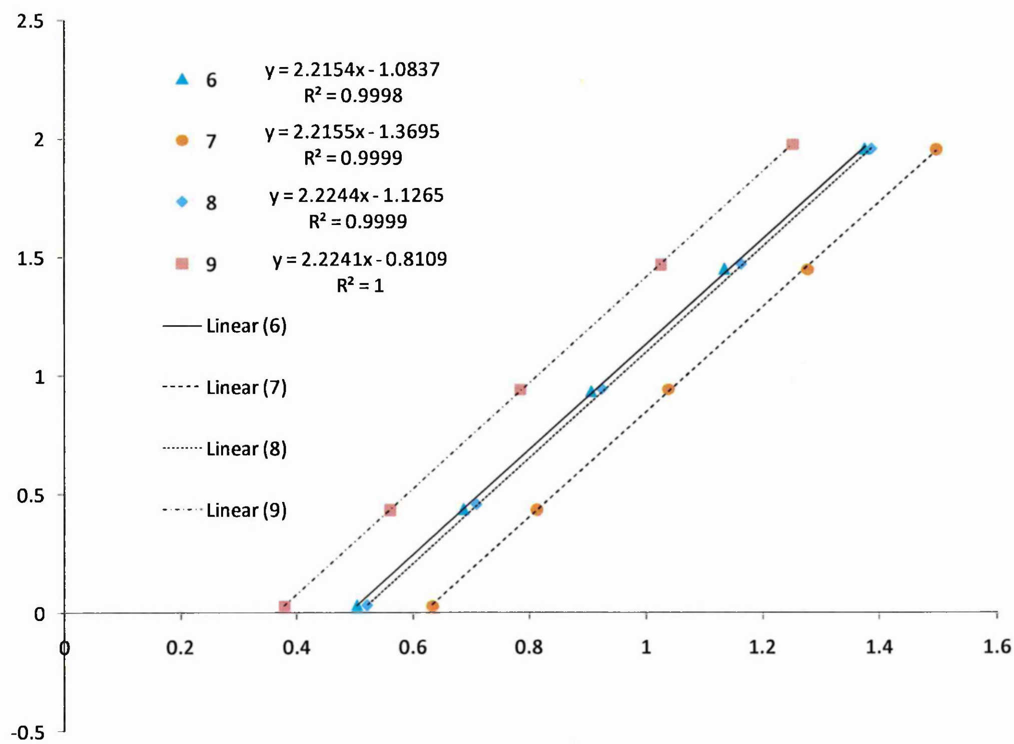

Figure D.4: Calibration data, regression line and regression equation for sensors with ID numbers 6, 7, 8, and 9 used within this research.

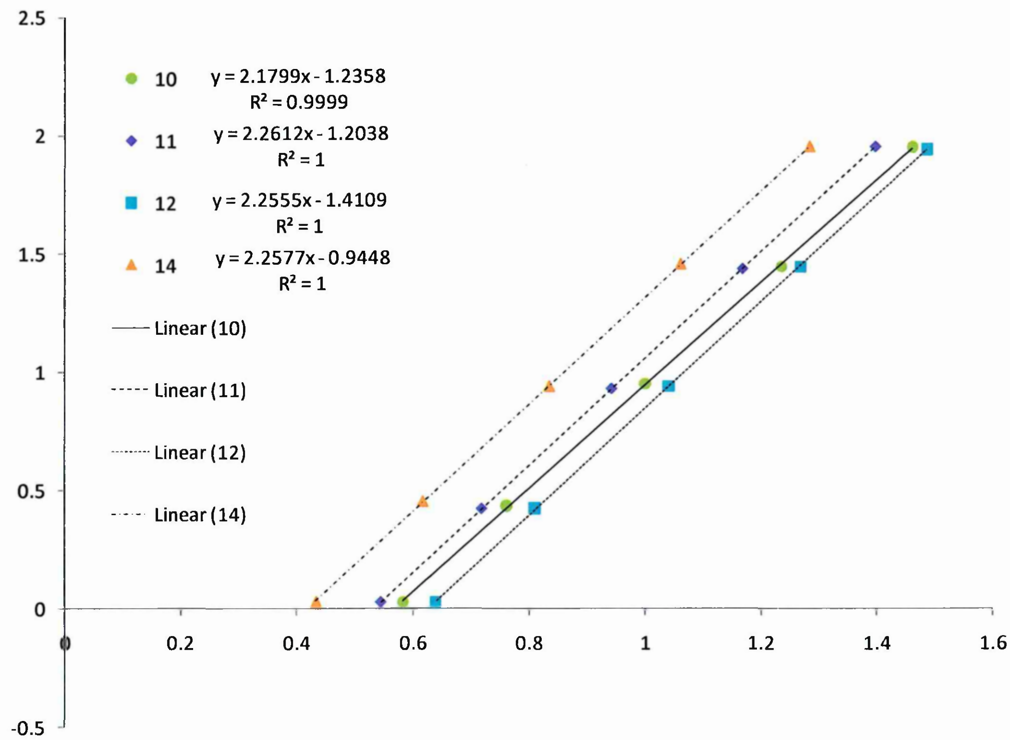

Figure D.5: Calibration data, regression line and regression equation for sensors with ID numbers 10, 11, 12, and 14 used within this research

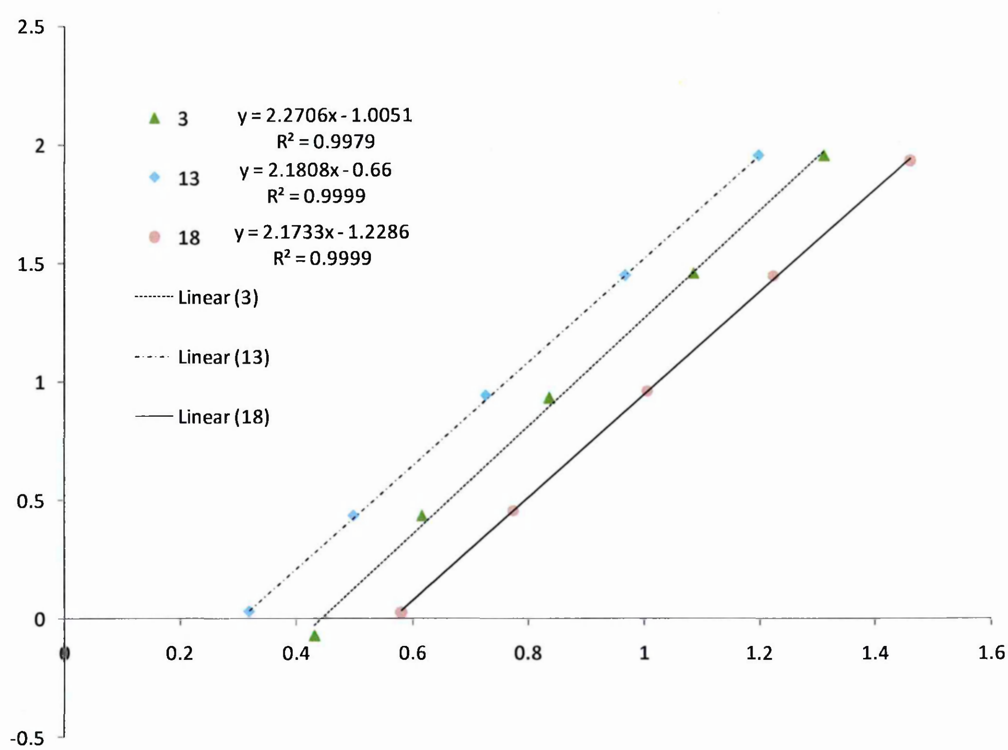

Figure D.6: Calibration data, regression line and regression equation for sensors with ID numbers 3, 13, and 18 used within this research

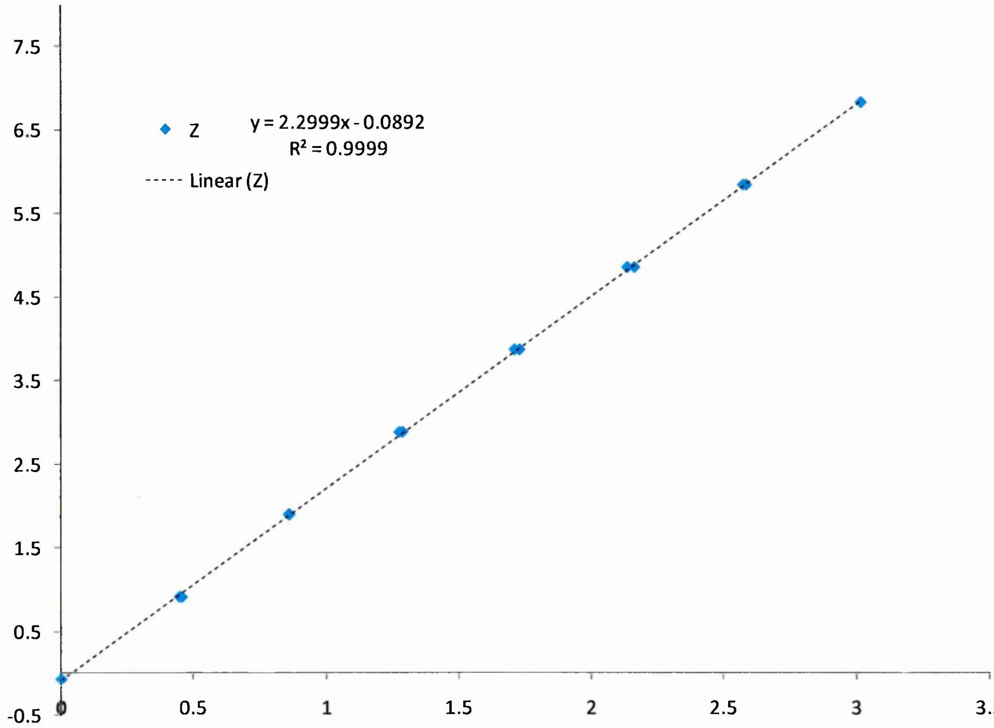

Figure D.7: Calibration data, regression line and regression equation for sensor with ID letter Z used within this research

Appendix E: Buried Artefact Breakage Method Development

E.1 Background

Prior to the breakage work done on the handmade replicate pots and aged human bones, the instrumentation methods, tyre configurations, and trial specifications – all the experimental methodology – needed to be developed and/or verified. Because the replicate pots and human bones were too valuable to use up in pilot testing, they were saved and modern terracotta garden pots were used as pseudo-artefacts. This section will outline the above methodology development. The results from the pilot testing of the modern terracotta pots are included as well, as these may be useful in the future as a comparative feature for other, more recent archaeological deposits buried within cultivated fields.

E.2 Methodology Development

The instrumentation technique used to allow breakage detection was first created in Dain-Owens, 2006. This work pioneered the use of a painted-on conductive trace that would break at the same instant as a modern terracotta pot. The research used static loads to test the instrumentation (as opposed to dynamic loads). The modern terracotta pots used for the test were much smaller. The pots were instrumented and buried alongside pressure sensors in a soil tank (as opposed to a soil bin), and the tests performed only to verify that the instrumentation system was functional, with potential for use on other brittle buried objects.

Dain-Owens (2006) also did a unique preliminary study to determine where on the pot the conductive traces should be placed, in order to maximize the efficiency of the breakage detection. Two breakage zones were chosen for the instrumentation system: The rim and the body of the pot for horizontally and 45-deg orientated pots; and the rim and the bottom of the pot for vertically orientated pots.

The pilot testing in this section utilized the two-zone conductive trace system. The attached wires and circuit board configurations were slightly modified for durability and ease of use. Multiple trials performed in a full-length soil bin with a soil processor and tyre rig attached to it required the use of longer and more durable wires, as the data logging system was situated farther away from the buried objects and sensors, and there was a higher level of hazard for wires getting cut or otherwise damaged. The circuit board receiving the electrical signals from the buried pots needed restructuring, to accommodate up to 9 pots each with two circuit traces. Because of the higher number of data loops, different data loggers were used and the computer's software configuration receiving the data from the logging system was also altered. These changes did not affect the burial and trial testing procedure; they were only done to adjust the breakage detection and data logging system to the change from static loading in a small space to dynamic loading in a large space. These changes were made in the early stages of pilot testing, as the data collection system was essential for the other aspects of the trial methodology development.

The pots used throughout the pilot testing with the exception of the last pilot test (number 5), were modern terracotta pots, approximately 23 cm wide at the mouth, 14 cm wide at the base, 22 cm tall, and 4 mm thick. The pots used for the fifth pilot test were approximately 14 cm wide at the mouth, 9 cm wide at the base, 13 cm tall, and 4 mm thick. The ceramic membrane pressure sensors were the same as those used in the main trials with replicate pots and human bone. The sensors themselves were 19 mm in diameter with a 10 bar limit, and were mounted into an aluminium cylinder of dimensions 20 cm length, 7 cm diameter.

Five pilot trials were conducted. In each pilot trial, nine terracotta pots were buried in the soil bin along the central axis. Three pots were buried horizontally orientated, three were buried at 45°, and three were vertically orientated (see Figure E.1). The ceramic strain gauge pressure sensors were orientated perpendicularly to the soil surface and buried alongside the pots, in-line and at the same depth.

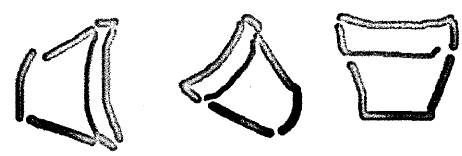

Figure E.1: Terracotta pot orientations.

Left to right – horizontal, 45°, vertical.

Pilot Trial 1 and Pilot Trial 2 were both done using a range of surface loads using tyres with inflation pressures and loadings similar to those in conventional agriculture. This range of tyres was compromised of small, soft tyres at light loads, middle range tractor tyres at conventional loads, and larger heavy duty tyres at higher inflation pressures and higher loads, each load-inflation case chosen from a 'real-life' situation.

Starting with Pilot Trial 3, only one tyre was used. This was changed in order to simplify procedure and maximise efficiency of the study. Using a range of tyres meant that every run the entire laboratory setup had to change – tyre rig, tyre, loading. This took a very long time in the laboratory, and required much technician support. For multiple tests the procedure was proving to be too difficult to maintain. The efficacy of the study was maximised as well, since by using one tyre and modifying inflation pressure and load, more controlled changes in the subsurface pressure propagation was possible.

Stress concentrations from the tyre lugs were still a source of unknown variability that might be interfering with pressure transfer. Taking this into consideration, the lugs were stripped off of the tyre in Pilot Trial 3, and this smooth tyre was used for all pilot and real trials thereafter. The specifications of all the tyre-inflation-load configurations for all pilot trials are shown in Table E.1.

The single tyre (600/55-26.5 Trelleborg T421) was chosen before Pilot Trial 3 as a multi-purpose agricultural-type, with its ability to run safely at low pressures and low loads as well as high pressures and large loads. Using the tyre manufacture chart as a base, a load inflation plan for the successive tyre runs was created. Only six runs were included (versus eight runs that had been previously used for Pilot Trial 1 and Pilot Trial 2), as no pots had broken in the lower subsurface pressures generated by lighter and less-inflated tyres. Using six runs was an important modification to the trial procedure, as this relieved the soil of two tyre runs, lessening the compaction caused within the trials from multiple passes.

The load-inflation specifications for the laboratory testing were decided to be the manufacturer's recommended pressure with one tonne less load than set forward in the manufacture load/inflation chart. This was done to generate similar magnitudes of pressure at depth as had been seen from the range of tyres used in trials one (1) and two (2). It was also done in order to achieve a more evenly-spread range of peak pressures per run within each trial. This would enable the pressure threshold, or breaking point, of the buried objects to be better identified.

Table E.1: Experimental specifications for Pilot Trials

Pilot Trials	Run #	1	2	3	4	5	6	7	8
Multiple Tyres: Pilot 1	Tyre	ATV	Terra	Tractor	Tractor	-	Harvester	Harvester	Truck
	Pressure (bar)	0.3	0.7	1.0	2.0	-	2.0	2.0	6.9
	Load (tonne)	0.16	3	1	2	-	5	10	5
Multiple Tyres: Pilot 2	Tyre	ATV	Terra	Tractor	Tractor	Harvester	Harvester	Harvester	Truck
	Pressure (bar)	0.3	0.7	1.0	2.0	1.0	2.0	2.0	6.9
	Load (tonne)	0.16	3	1	2	5	5	10	5
Single Lugged Tyre: Pilot 3	Tyre	-	-		Trelleborg Agricultural Cross-Ply Implement Tyre 600/55-26.5 Tread T421				
	Pressure (bar)	-	-	0.5	1.0	1.5	2.0	2.5	2.8
	Load (tonne)	-	-	1.7	2.8	3.8	4.9	5.9	6.5
Single Smooth Tyre: Pilot 4	Tyre	-	-		Trelleborg Agricultural Cross-Ply Implement Tyre 600/55-26.5 Tread T421				
	Pressure (bar)	-	-	0.5		Pressure (bar)	-	-	0.5
	Load (tonne)	-	-	1.7		Load (tonne)	-	-	1.7
Single Smooth Tyre: Pilot 5	Tyre	-	-		Trelleborg Agricultural Cross-Ply Implement Tyre 600/55-26.5 Tread T421				
	Pressure (bar)	-	-	0.5	1.0	1.5	2.0	2.5	2.8
	Load (tonne)	-	-	1.7	2.8	3.8	4.9	5.9	6.5

E.3 Results

The results of all Pilot Trials are shown in Figure E.2, Figure E.3, and Figure E.4. Each figure includes the peak subsurface pressures recorded in each run of every Pilot Trial. Figure E.2 compares them with the lowest peak subsurface pressure under which the horizontally orientated pots began to break. It was discovered that the horizontal pots were always the first to break, due to their orientation putting them in the most vulnerable position. They also seem to break at relatively similar pressures to each other. The ranges of low-limit pressure thresholds for the 45-degree and vertically orientated pots are much larger than that of the horizontal pots. Figure E.3 does the same as Figure E.2 however it shows the lower limits of breakage for the 45-degree orientated pots; Figure E.4 shows the breakage for the vertically orientated pots.

In Figure E.2, Figure E.3, and Figure E.4, it is possible also to see the positive results of the tyre and laboratory specification methodology development. Pilot Trial 1 and Pilot Trial 2 are very similar – as they were both using similar tyres and specifications. Run 5 was added in Pilot Trial 2 as there was a need to create smaller pressure progression steps within the trial. Pilot Trial 3 was the first to use only one tyre and six runs. The subsurface pressures resulting were very similar to runs # 3 – 8 in Pilot Trial 1 and Pilot Trial 2. Pilot Trial 4 was the first to use a smooth tyre. The pressures in this trial seem lower than the rest, which is most likely a product of a mistake in the soil preparation. This was fixed however in Pilot Trial 5, with the pressures again similar to the first three Pilot Trials. It was at this point that the experimental methodology and trial procedure was deemed suitably reliable and durable for testing with the handmade replicate pots and aged human bones.

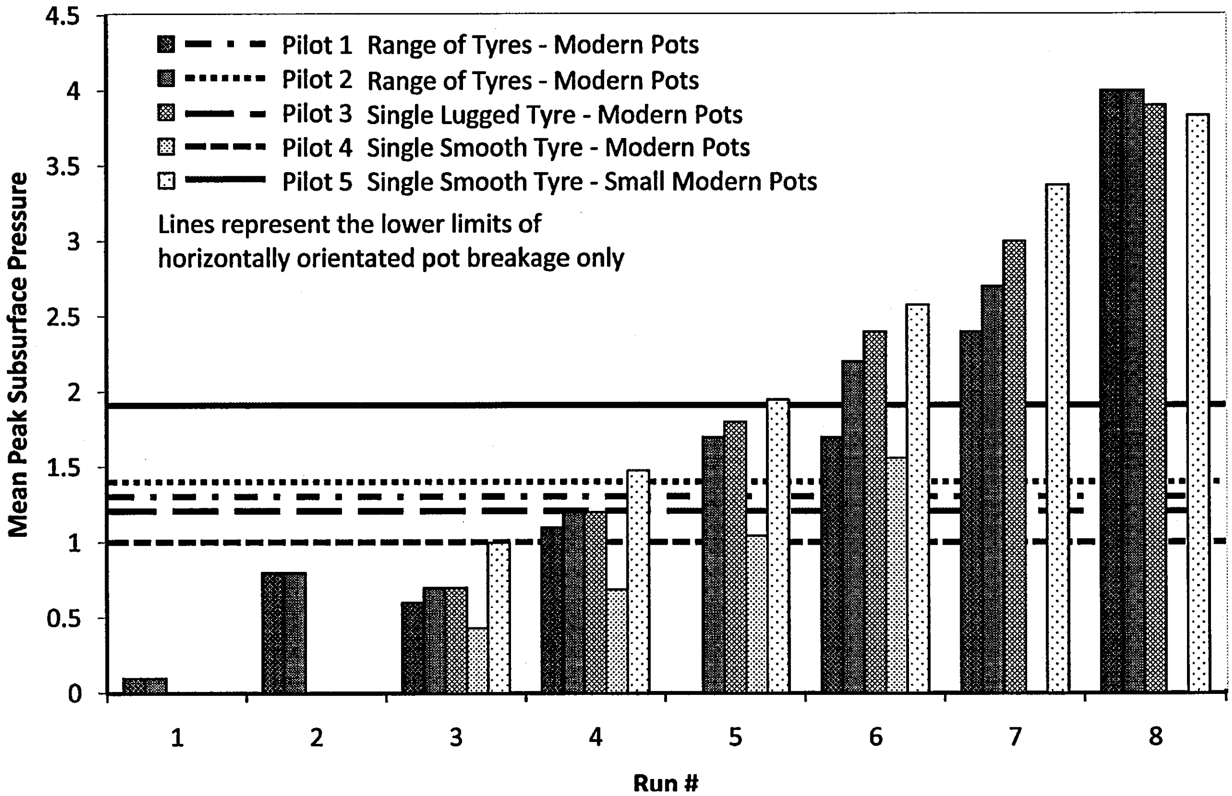

Figure E.2: The mean peak subsurface pressures and experimental subsurface pressure threshold values for horizontally orientated modern terracotta pots.

Two sizes of pots were buried in a sandy loam soil and subjected to surface loads from a range of differently loaded and inflated agricultural tyres. The lower limits of breakage are shown, representing the subsurface pressures at which the horizontally orientated pots began to break.

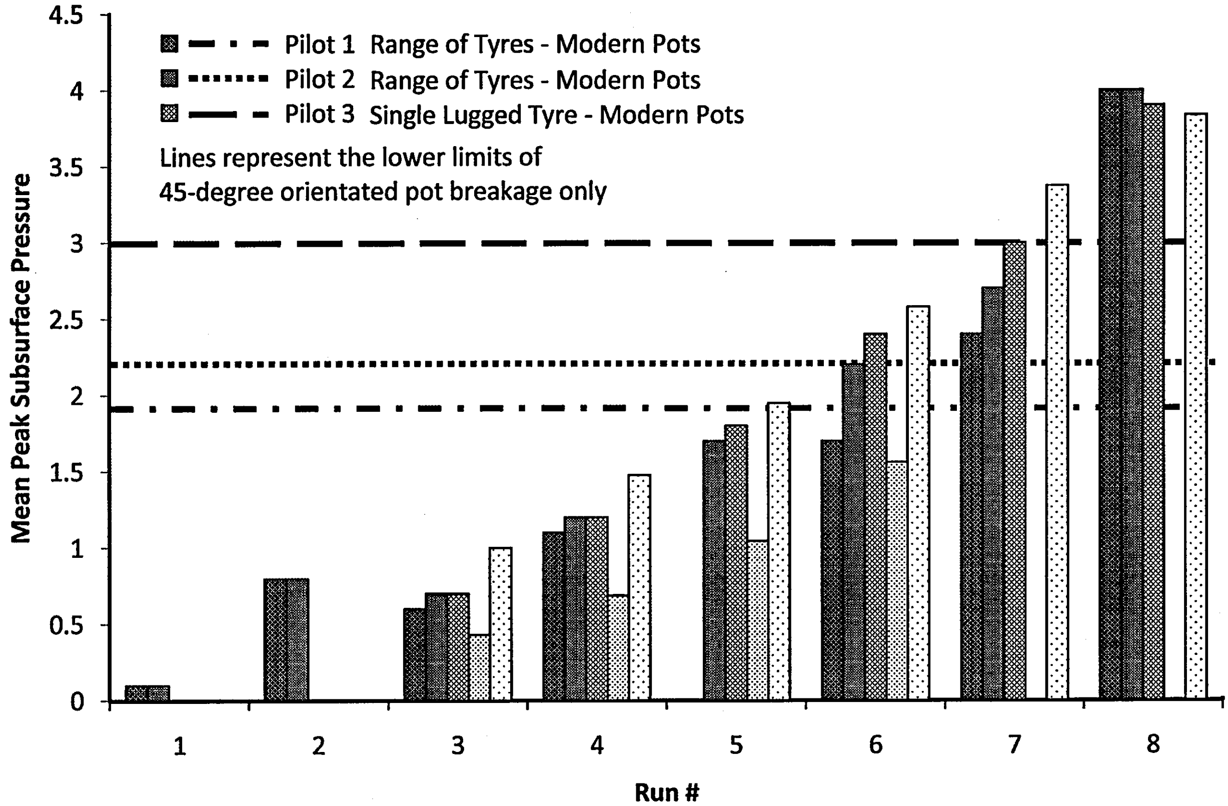

Figure E.3: The mean peak subsurface pressures and experimental subsurface pressure threshold values for 45-degree orientated modern terracotta pots.

Two sizes of pots were buried in a sandy loam soil and subjected to surface loads from a range of differently loaded and inflated agricultural tyres. The lower limits of breakage are shown, representing the subsurface pressures at which the 45-deg orientated pots began to break. Note that pressure data after the third run in Pilot Trial 4 does not exist, so breakage pressures for the 45-deg pots are unknown. Also, none of the 45-deg pots in Pilot Trial 5 broke, so results are not shown.

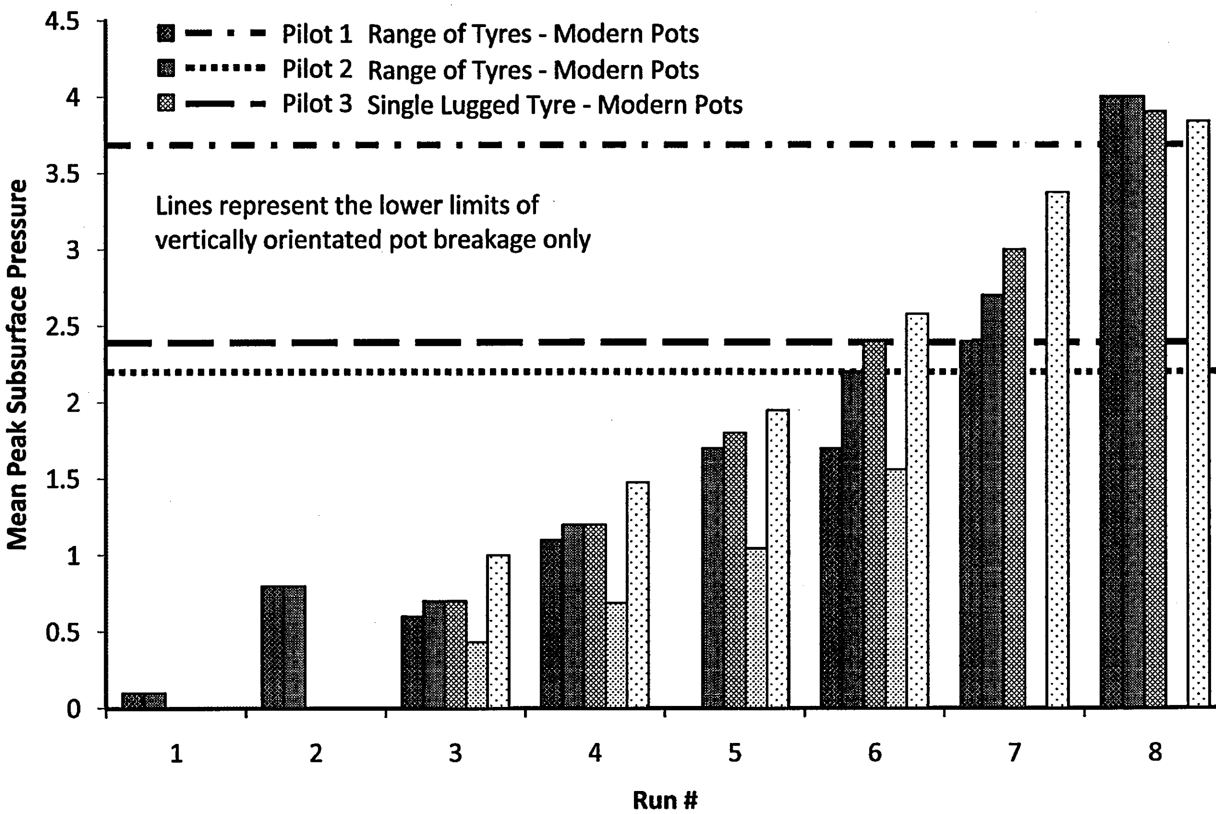

Figure E.4: The mean peak subsurface pressures and experimental subsurface pressure threshold values for vertically orientated modern terracotta pots

Pots were buried in a sandy loam soil and subjected to surface loads from a range of differently loaded and inflated agricultural tyres. The lower limits of breakage are shown, representing the subsurface pressures at which the vertically orientated pots began to break. Note that in Pilot Trial 4 and Pilot Trial 5, none of the vertically orientated pots broke (therefore there are no results shown here).

Table E.2 shows the breakage results from the trial in more detail.

Table E.2: Breakage data for each trial; refer to Table E.1 for tyre data.

Pilot Trial	Run	Breakage
1 Multiple Tyre (Modern Pots)	1	none
	2	none
	3	none
	4	none
	5	not included
	6	horizontal only
	7	45° only
	8	vertical only
2 Multiple Tyre (Modern Pots)	1	none
	2	none
	3	none
	4	none
	5	some horizontal
	6	remainder horizontal
	7	most 45° and some vertical
	8	remainder 45° and remainder vertical
3 Lugged Single Tyre (Modern Pots)	1	none
	2	some horizontal
	3	some horizontal
	4	remainder horizontal,
	5	most 45° and some vertical
	6	remainder 45° and remainder vertical
4 Smooth Single Tyre (Modern Pots)	1	none
	2	none
	3	horizontal only (rim + body)
	4	horizontal only (rim + body);
	5	45-deg pots only (rim)
	6	45-deg pots only (rim);
5 Smooth Single Tyre (Small Modern Pots)	1	none
	2	none
	3	horizontal only (rim)
	4	horizontal only (rim + body);
	5	none further
	6	none further

Note 1: In Pilot 4, none of the vertically orientated pots broke
Note 2: In Pilot 5, none of either the 45-deg pots or the vertically orientated pots broke

Regarding the breakage dynamics of the pots themselves, it was observed that similarly oriented pots always broke in similar manner. Figure E.5 shows photos taken during pot excavation. With the terracotta pots in the horizontal orientation, the rim always seemed to break first. The crack would then propagate through the body of the pot. The influence of the bottom of the pot on the ability of the terracotta material to resist the breakage seemed to have an effect 1/2 to 2/3 of the way down the pot. The crack then split into an upside-down Y-shape, ending at the bottom of the pot. The 45-degree orientated pot broke in a different fashion. Within the rim, four main cracks would appear, all almost perpendicular to each other. One crack would always occur at the top, one always at the bottom, and two more, always one on either side of the pot. The vertically orientated pot was the strongest orientation. With these pots, the bottom of the pot always popped out; the rest of the pot remained unbroken.

Figure E.5: Examples of broken pots and fracture patterns:

Left to right: Horizontal, 45°, Vertical.

E.4 Conclusions

The methodology development within five pilot trials was successful. The 'real' trials using the replicate pots and human bones were performed without any major problems, and the results were not compromised due to flaws in the procedures or instrumentation. Of course, there will always be room for improvement, and small issues due to the nature of experimental work, but overall, the methodology, specifications, and trials procedure were sufficiently established. The explanation of the entire finalized methodology lies within Chapter 3, which presents the object breakage laboratory work within this project.

The modern terracotta breakage results can be summarized as follows. The lowest breaking peak subsurface pressures were:

- 1.0 bar for the horizontally orientated pots;
- 1.9 bar for the 45-degree orientated pots; and
- 2.2 bar for the vertically orientated pots.

The horizontally orientated small modern terracotta pots (in Pilot Trial 5) broke at 1.9 bar peak subsurface pressure. Neither the 45-degree nor the vertically orientated pots broke within this last Pilot Trial 5, and it can be concluded that the peak subsurface pressures were not high enough to cause pot failure.

The typical fracture patterns of the modern terracotta pots were noted, with a upside-down Y-shape pattern with cracking starting in the rim and propagating thus through the body in the horizontal pots, perpendicular cracks on the top, bottom, and sides of the pot rim propagating into the pot body for the 45-degree pot, and the bottom popping cleanly away from the body for the vertically orientated pots.

Appendix F: OA Report Appendix 1

Appendix 1
Sub-soil pressures resulting from tillage implements and vehicle loads

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Appendix 1
Sub-soil Pressures Resulting from Tillage Implements and Vehicle Loads

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Appendix 1
Sub-soil Pressures Resulting from Tillage Implements and Vehicle Loads

1 INTRODUCTION

1.1 Background

1.1.1 Buried archaeological features, deposits and related artefacts and ecofacts are found at varying depths in the soil profile, and as such can be subjected to a variety of different loads from tractors and implements working in the fields. These loads and the resulting soil pressures can cause damage to both the soil structure and the buried archaeology. The aim of this part of the study was to investigate the pressure that a range of tillage implements and vehicle loads, transmitted via both tyres and rubber tracks, exert on buried objects. The purpose of this is that data on these pressures can subsequently be related to the potential archaeological damage caused by a range of subsoil pressures reported in later Appendices.

1.1.2 It is important to understand the effects of both tillage tools and their respective tractor sizes. Potentially, the weight of a 300 hp (12 t) tractor used for wide shallow-tillage operations will cause greater subsoil pressure/disturbance and hence damage to buried archaeological deposits than a 150 hp (6 t) tractor pulling a smaller width mouldboard plough at greater depth. Combine harvesters and pea harvesters now weigh in excess of 25 t, with some sugar beet harvesters approaching 55 t. The tyre systems fitted to these machines may be sufficiently large, with lower inflation pressures, to result in less soil damage compared to lighter machines on smaller section tyres. However, this depends upon the combination of both load and the surface contact pressure (Soehne 1958). The surface contact pressure from pneumatic tyres is a function of both the tyre inflation pressure and the effect of the carcass stiffness (Chancellor 1976; Plackett 1984; Misiewicz *et al.* 2007; 2008). As a result it can be shown that it is vehicles equipped with high inflation pressure tyres (up to 7 bar) with high carcass stiffnesses, specifically designed for high speed road going trucks, that are most likely to impart maximum soil pressures. Unfortunately because of their relatively small size and ease of availability on the second hand market such tyres may be fitted to farm-built trailers. At the other end of the spectrum rubber tracks do help to spread the load of high horsepower tractors (10-25 t), combine harvesters (32 t) and sugar beet harvesters (25 t) as shown by Ansorge and Godwin (2007; 2008) (Figure 1.1). In this figure the lengths of the arrows represent the amount of soil deformation at each location and show that the extent of soil displacement at depths to 600 mm deep are reduced by a factor of two by the use of rubber tracks.

1.1.3 The soil engaging components of individual tillage implements would be expected to cause relatively low subsoil pressures, especially on primary tillage implements (chisel tines, mouldboard plough shares and blades) with low rake angles (see Figure 1.2), as these are designed to lift and loosen the soil. These implements with rake angles of approximately 20-25° produce an upward vertical force on the soil, as shown in Figure 1.3. These forces are then transmitted to equal and opposite forces acting on either the depth control wheels of the implement tool bar and/or the tractor wheels. The only direct downward force from these tools would be generated from the worn underside of the leading tip which can have rake angles in excess of 120-

150°. Implements such as furrow press rings, rollers, discs and wheels that are designed to both roll and crush soil surface aggregates produce the larger downward vertical forces on the soil. This is because they are effectively high rake angle implements and by nature of their requirement are generally heavy. In contrast the vertical tines of drag and power harrows, which are designed to rearrange and also break surface aggregates, produce only small downward forces as shown in Figure 1.3.

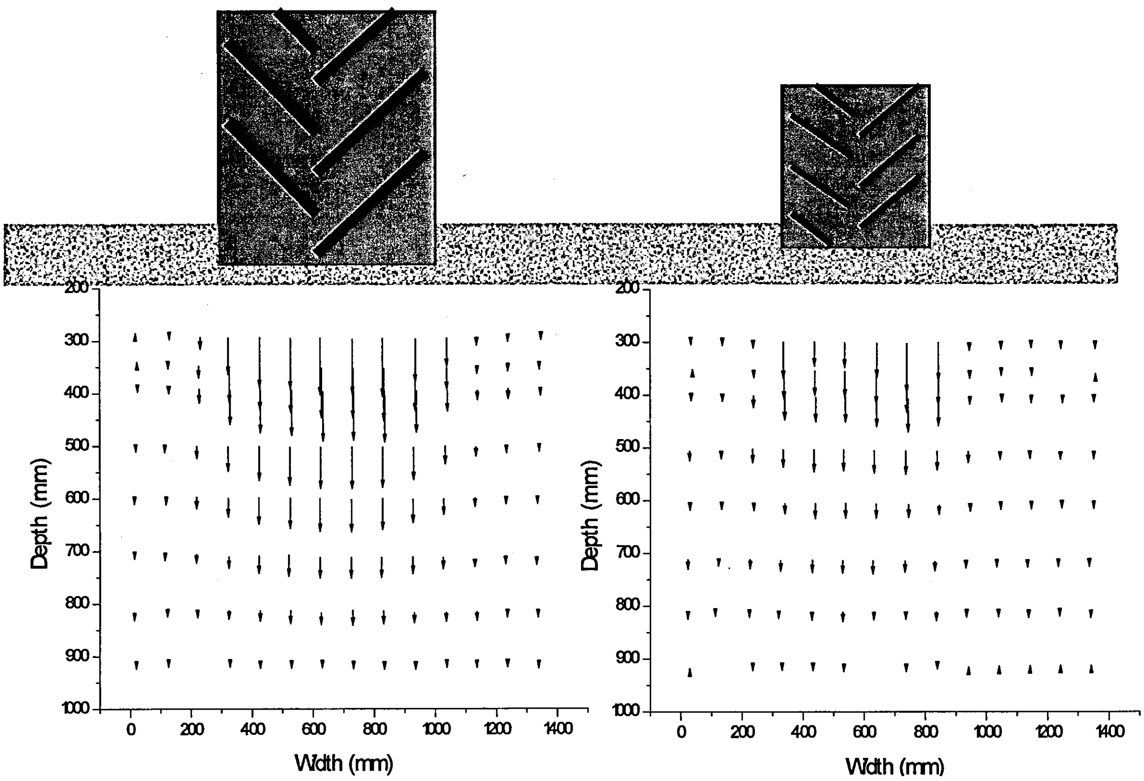


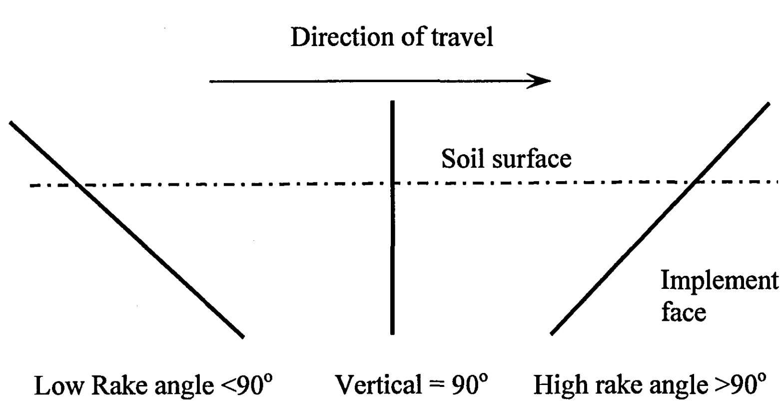
Figure 1.1.Comparison of the soil deformation under an 800 mm wide tyre (left) and 650 mm wide rubber track (right). (Ansorge and Godwin 2007)

1.1.4 Little research has been reported on the pressures below individual tillage implements; whilst many studies have been conducted on soil pressures below tyres and tracks (Reeves and Cooper 1960; Arvidsson *et al.* 2001; Keller and Arvidsson 2004; Raper and Arriaga 2005; Lamande *et al.* 2006; Ansorge and Godwin 2007; 2008). Furthermore van den Berg and Gill (1962) have studied the pressure distribution on smooth tyres; however, there is no comparative information for the range of tyres and tracks currently used in agriculture in the UK.

1.1.5 Since the pioneering work of Boussinesq (1885) a number of studies have attempted to predict the stress levels and distribution in the soil under tyres and tracks. The study by Soehne (1958) was very valuable in comparing the effect of contact pressure and applied load; this work concluded that contact pressure influenced the level of soil stress and the magnitude of the load determined how deep that level of stress penetrated into the soil. However, both Soehne (1958) and Schafer *et al.* (1992)

indicate that there are key problems with characterising the elasto-plastic nature of soil in obtaining predicted stress levels that match those recorded in field studies. More recent prediction models such as COMPSOL (O'Sullivan *et al.* 1998) and SOILFLEX (Keller *et al.* 2007), which are based on critical state soil mechanics principles, provide relatively easy methods to compare different wheel/tyre pressures providing the correct virgin compression line data are available. However, recent studies by Ansorge and Godwin (2009) showed that obtaining these data is problematic.

1.1.6 To determine the soil pressures for a current range of equipment there is no alternative but to measure directly the pressures from surface applied loads acting on buried pseudo artefacts. This was done by installing pressure transducers into both flat plates and cylindrical vessels which simulate the tops of submerged rigid non-deformable walls and buried displaceable pots respectively. These pseudo artefacts were buried at a range of depths in a sandy loam soil (Cottenham series; King 1969) in controlled laboratory conditions where it was easy to locate the necessary pressure sensors. A further limited range of studies where undertaken in a clay soil (Evesham (formerly Wicken) series; King 1969) in field conditions using only the cylindrical sensors.



Implements

Chisel tines	Harrows	Presses
Mouldboard plough shares	Drag	Rollers
Bulldozer blades	Power	Wheels and tyres

Figure 1.2. Optimal tine rake angles for a range of soil operations and basic implements. (Spoor 1969)

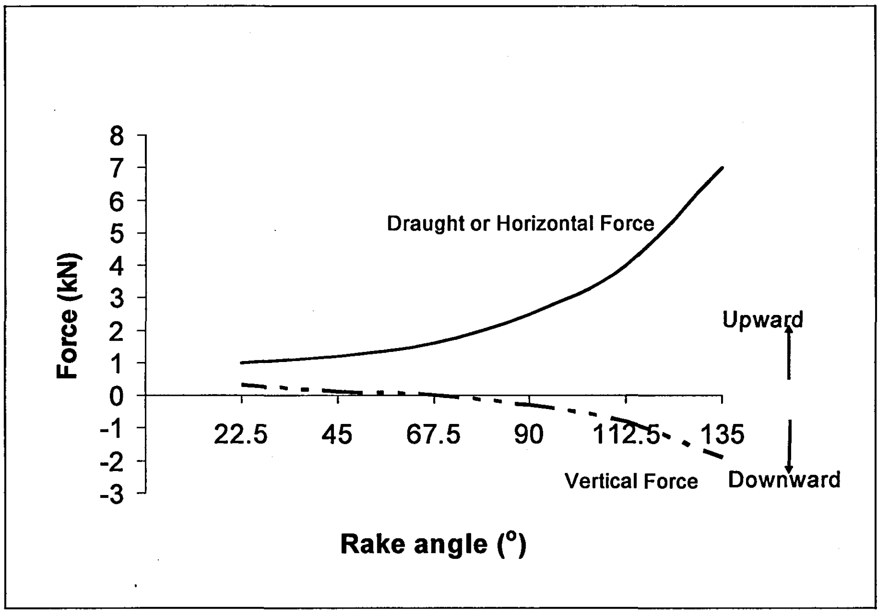


Figure 1.3 Relationship between rake angle and the magnitude and direction of soil implement forces. (Godwin 2007)

2 METHODOLOGY

2.1 Detailed laboratory studies in a sandy loam soil

2.1.1 This study was conducted under controlled soil conditions (moisture content 9+/-1%), in the 20 m long × 1.7 m wide × 0.9 m deep soil bin laboratory at Cranfield University at Silsoe, as shown in Figure 1.4, where the required soil conditions could be easily replicated with accurate position control of buried artefacts, tyres and tillage tools and loads. The laboratory is also independent of weather conditions.

2.1.2 The pseudo archaeological features and artefacts were buried at a range of depths below the soil surface and consisted of:

- a) buried plates (500 mm long, 125 mm wide and 12 mm thick) with a pressure sensor mounted flush on the upper surface (Figure 1.5 left) and
- b) 100 mm diameter aluminium cylinders (6 mm wall thickness) with a surface mounted pressure sensor, in the middle of the length, flush with the top surface (Figure 1.5 right).

2.1.3 The plates were rigidly mounted on the floor of the soil bin, intending to represent a feature such as a wall foundation that is constrained vertically within the soil profile, as illustrated in Figure 1.6. The aluminium cylinder was chosen as a proxy for a ceramic or glass object, as aluminium has a similar modulus of elasticity to common ceramic/glass materials (Gordon 1991), whilst being more robust for experimental use. The cylinder represents a buried object, such as a pot or bottle, that depending upon the relative pressure above and below the cylinder could be displaced downward within the soil profile. The position of the single sensing element on the cylinder was determined by work by Chalvantis (2005) which indicated that the maximum pressure acting on the surface of a horizontally buried cylinder coincides with the centre line of the top surface.

Figure 1.4. Soil bin laboratory showing both a rubber track (left) and combine harvester front tyre (right). (Ansorge and Godwin 2008).

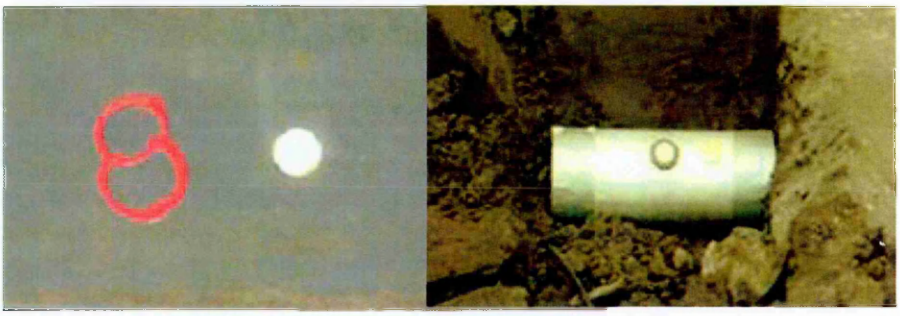


Figure 1.5. Plate (left) and cylinder (right) both with ceramic pressure sensors embedded in upper surface (the sensor in plate is numbered 8).

2.1.4 The pressure transducers selected were 19 mm diameter (10 bar) ceramic membrane types (PT19, Applied Measurements, Berkshire, UK). The instrumented plates and cylinders gave information relating to pressures experienced at the soil/object interface at specific depths within the profile. The sensors were calibrated using compressed air, referenced to a traceable dead weight pressure standard. Electrical signals from the pressure transducers were conditioned and logged to a PC using an FE-MM8 datalogger (Fylde Electronics, Lancashire, UK). The data were collected at 5 kHz and reduced to 500 Hz by taking a block average for convenient data storage.

2.1.5 The intention is that these pressure data will be used with pressure threshold data collected and reported in the following appendices concerning the failure of buried artefacts in order to identify the types of agricultural practice and depth of artefact burial where damage may occur. For each specific preparation, the sensors were positioned along the central axis of the soil bin at the depths shown in Figure 1.6. The sensors were located in the topsoil of a Cottenham series sandy loam compacted with 6 passes of the soil bin processing roller to a dry bulk density of 1.60 +/- 0.10 g cm^3 and then a further 250 mm of soil placed on top which was compacted to 1.48 +/- 0.08 g cm^3 to simulate a topsoil layer which, under arable conditions, will have been tilled to that depth within recent history, and will therefore have a dry bulk density lower than that of the subsoil. Due to budgetary and physical constraints only the sensors at depths of 250 mm were replicated (3 times). This depth was selected as the shallowest practical position for the sensors, as in the field artefacts at a shallower depth would most probably have been damaged by previous tillage operations. Concurrent with the shallowest depth we expect to record the highest resulting soil pressures. A further plate and cylinder sensor were placed at depths of 25 to 50 mm below the designated working depth of any tillage tool that operated at a depth shallower than 250 mm.

2.1.6 The repeatability of the data from the 3 sensors at 250 mm depth was acceptable, giving least significant difference (LSD) values at the 95% confidence interval of 0.058 and 0.74 bar for the tillage tools and the tyre and track systems respectively. On this basis the authors were sufficiently confident that a single replicate was sufficient for the less important deeper sensors where the resulting pressures were lower[1].

2.1.7 The studies involved investigations into the effects of:-

- a range of tillage implements, at depths typical of those currently used in arable farming
- a range of tyre and rubber track loads and tyre inflation pressures for tractors, harvesting machinery, trailers and trucks

2.1.8 These are listed in Table 1.1 and shown in Figures 1.7 and 1.8. The investigation was conducted at a forward speed of 2 m/s (7km/h).

[1] It would have been physically impossible to have replicated each depth as the soil bin would have either been "saturated with sensors" with little space for soil between them (together with increased capital costs) or the work replicated three times increasing the overall costs of this section by a factor of 3, when the project was already under tight financial constraints.

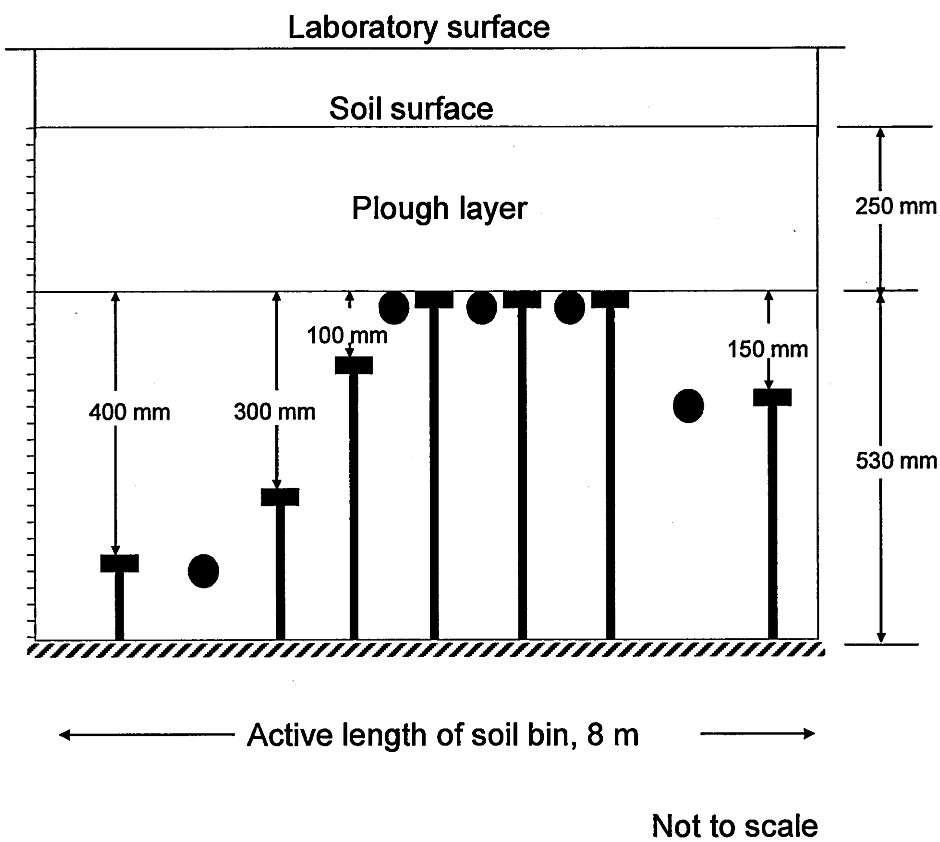


Figure 1.6. Pressure sensor type, relative position and depth of placement in the soil bin laboratory.

Table 1.1. Tillage implement and tyre/rubber track configurations used in the laboratory study.

Tillage implement	**Depth of operation (mm)**
Mouldboard plough body	225 and 125
Furrow press	Surface
Direct drill coulter	75
Heavy roller	Surface
Direct drill tines	75
Root harvester share	200
Chisel tines	150
Light disc harrows Subsoiler tine	100 400
Simba DD ring presses	Surface
Tyres and rubber tracks	Tyre/Track size - Load (t) @ inflation pressure (bar)
High speed road - truck tyre	Goodyear G159 385/65 R22.5 - 5 @ 7
Single rear axle tractor tyre	Firestone WTR 480/70 R34 - 2 @ 1
Single rear axle tractor tyre	Firestone WTR 480/70 R34 - 2 @ 2
Dual rear axle tractor tyre	TWO tyres 16.9/14-30 (X ply) - 2 @ 1
Combine harvester tyre	Continental 800/65 R32 - 10 @ 2
Combine harvester tyre	Continental 800/65 R32 - 10 @ 1
Combine harvester tyre	Continental 800/65 R32 - 5 @ 1
Combine harvester tyre	Continental 800/65 R32 - 5 @ 2
Rubber track	Claas Terra Track - 5 @ n/a
Rubber track	Claas Terra Track - 10@ n/a

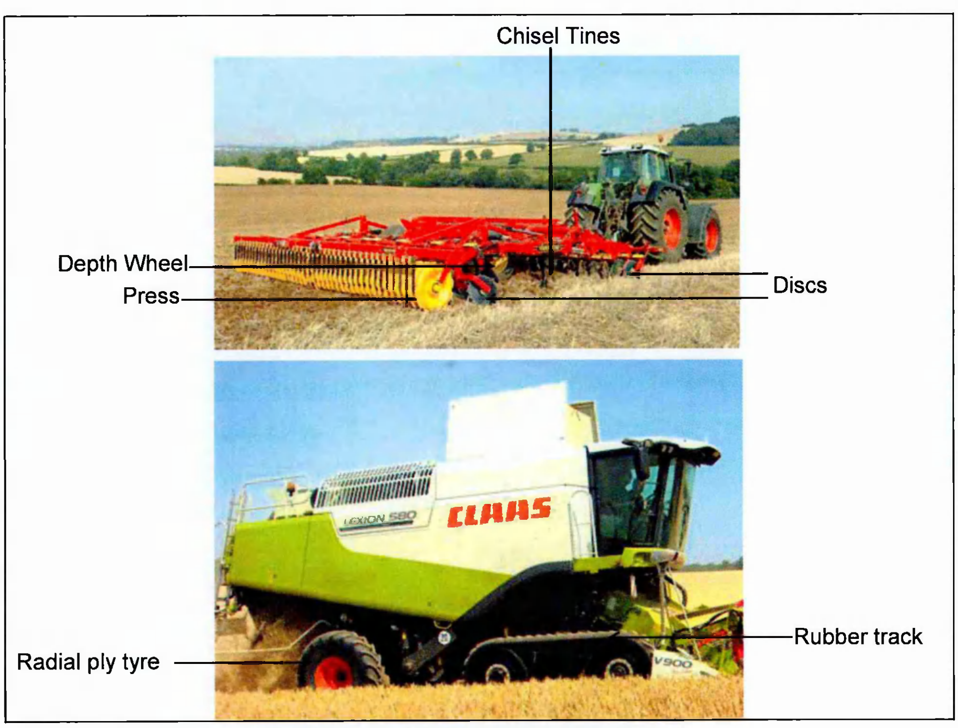


Figure 1.7 A typical "combination" tillage implement (upper) illustrating many of the individual components studied and a combine harvester (lower) equipped with rubber (Terra) tracks and radial ply tyres on the front and rear axle respectively.

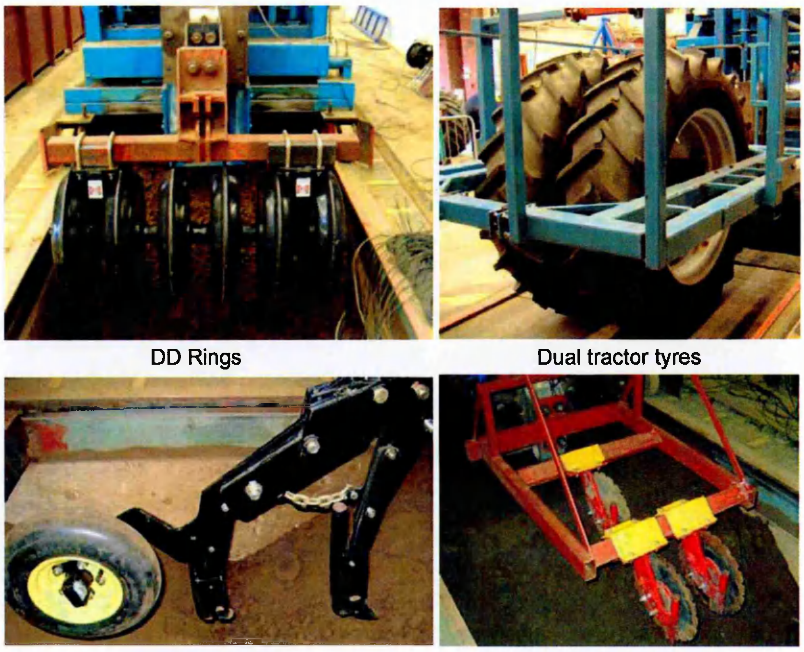


Figure 1.8. DD Rings, dual tractors tyres, direct drill coulters and direct drill tines in the soil bin laboratory prior to investigation.

2.2 Field studies in clay soil

2.2.1 These studies were conducted in an Evesham series (formerly Wicken series (King 1969)) clay soil on the Cranfield University Farm at Silsoe using 12 cylinder-mounted sensors in 3 banks of 4 cylinders at the depths shown in Figure 1.9. The cylinders were inserted into the clay by digging an access pit, augering 125 mm diameter holes 500 mm into the pit face, inserting the 100 mm diameter cylinders *c* 0.50 m along the hole and packing the free space above the cylinders with clay in a plastic state. The holes and the access pit were then backfilled and compacted to as near an original condition as possible. Care was taken to locate the position of the cylinders against suitable benchmarks.

2.2.2 The cylinders were inserted in October when the soil had a plastic constituency; they were then left until the following September to allow the soil to recover and to have field conditions similar to the arable farming conditions during harvest and the subsequent autumn tillage season. As it was not possible to undertake individual passes of individual wheels/tyres on previously non-trafficked soil, as conducted in the soil bin, a sequence of events was chosen where the load/pressure was increased with ascending levels of severity. These were conducted at a forward speed of 2m/s (7km/h). Full details of these are given in Table 1.2 and examples of the single, dual and terra tyres used are shown in Figure 1.10. A further set of studies was carried out in the following May when a rubber tracked combine was available.

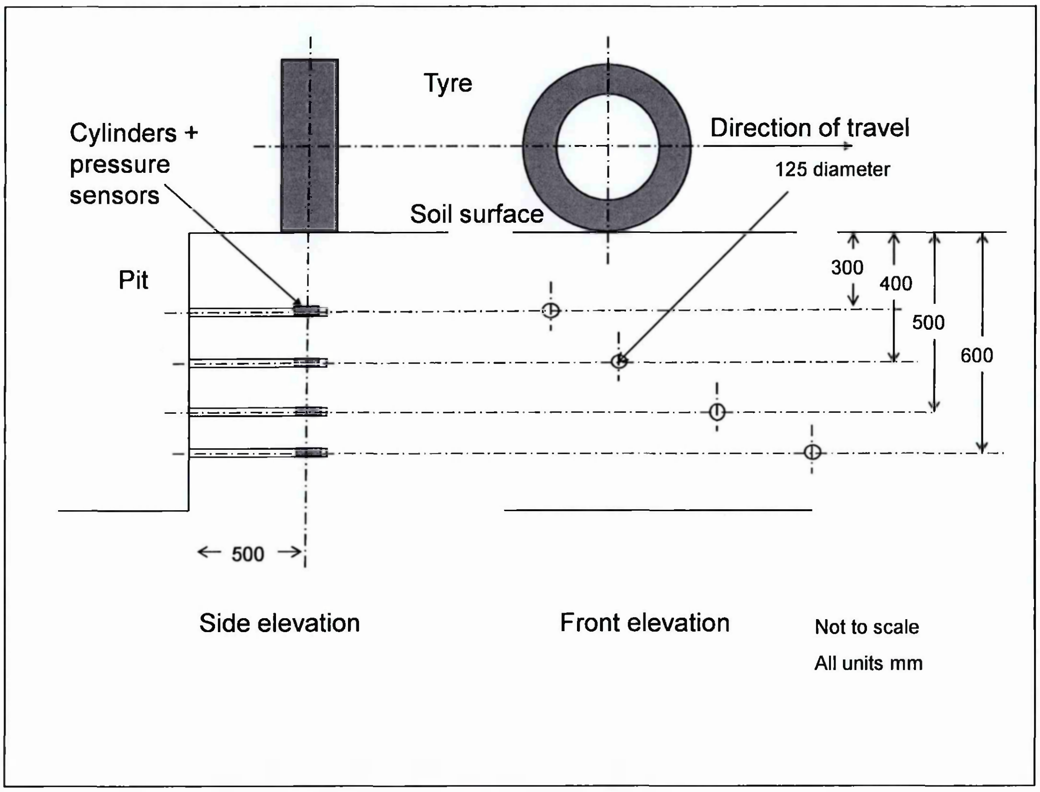


Figure 1.9. Details of the positioning of the cylinders and pressure sensors in the clay soil. Format replicated 3 times.

Figure 1.10. Single, dual and terra tyres used in the clay field experiment.

Table 1.2. Sequence of machine passes over the sensors located in the clay soil.

Load	Total Load kg	Size	Pressure bar
Human walking	90	-	-
Terra tyre – Ford 5610 Tractor	3300	400-17.5: 66x43.0-25	0.70 0.60
Dual tyres – MF 390 Tractor	4100	7.5-16.8 two, 13.6 R38	1.00 1.10
Single tyre - Pick-up Truck	1500	205-60R16	2.25
Single tyre -. MF 390 Tractor	3800	7.5-16.8 13.6 R38	1.00 1.10
Single tyre – Fendt 816 Tractor + raised 5 tine subsoiler (Sept only)	12700 + 2000	540/65 R28 650/65 R38	1.10 1.20
Rubber Track - Claas 580 Lexion Combine Harvester (May only)	22000	Terra track: 600/55-29.5	n/a 1.90
MF 390 Tractor + Tandem Axle Trailer	3800 + 8600	7.5-16.8 13.6 R38 12.5/80 x 15.3 12.5/80 x 15.3	1.00 1.20 2.50 2.50

3 RESULTS AND OBSERVATIONS

3.1 Laboratory studies in sandy loam soil

3.1.1 Typical raw pressure data from the cylinder sensors under a mouldboard plough are shown in Figure 1.11. This demonstrates the sensitivity of the pressure sensors to small changes in soil pressure which rises to 0.03 bar as the share passes over the sensor, followed by the lifting effect of the implement reducing the pressure to -0.11 bar which then stabilises to -0.02 bar, where the reduction in quasi-static pressure is due to the removal of the furrow slice.

3.1.2 Similarly, Figure 1.12 shows the effect of an 800 mm combine harvester tyre with a 10 t load and 1 bar inflation pressure. This shows the effect of the tyre on sensors at a range of depths and demonstrates that the recorded pressure reduces with depth. The data also support the argument by Chancellor (1976), Plackett (1984) and Misiewicz *et al.* (2007; 2008) that the surface contact pressure is equal to the inflation pressure plus a carcass stiffness effect. According to the method using tyre manufacturers' data described by Misiewicz *et al.* (2007), the pressure of a 900 mm section width tyre could be of the order of 2.0 bar, giving a total surface contact pressure of 3.0 bar, 0.6 bar of which is dissipated over the top 250 mm of soil depth, resulting in the peak pressure of 2.4 bar shown in Figure 1.12.

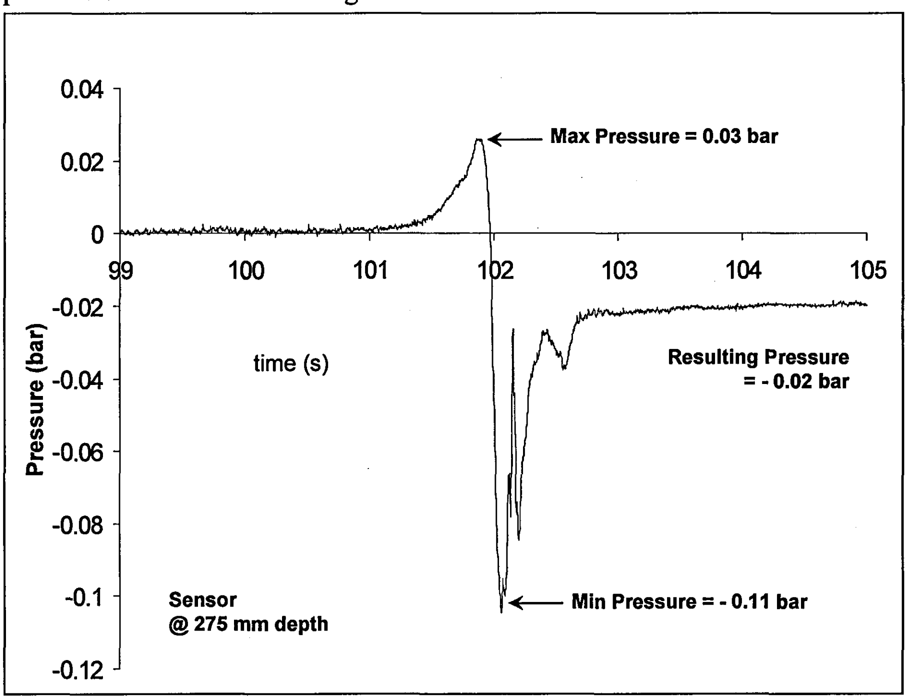


Figure 1.11. Pressure changes on a cylindrical mounted sensor situated 25 mm below the share depth of a mouldboard plough.

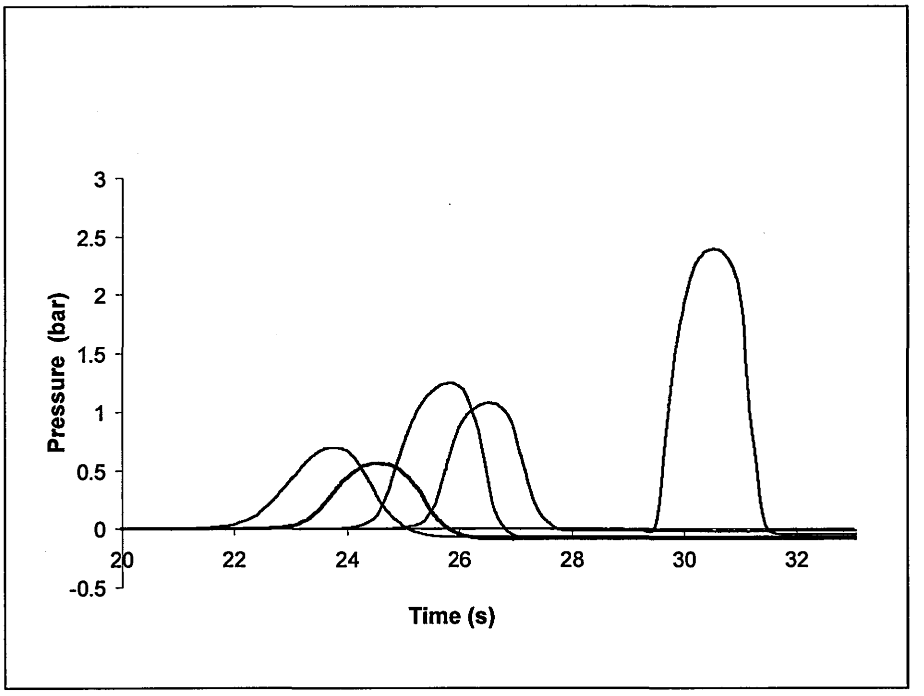


Figure 1.12. Cylinder pressure sensor data for an 800 mm wide combine harvester tyre at10 t load and 1 bar inflation pressure. The sequence of the outputs is from sensors located at 550, 650, 350, 400, and 250 mm from the soil surface

3.1.3 The factorial analysis of variance for both the data for the implements and the tyres/tracks showed that there was no significant overall difference between the pressure recorded on the plates and cylinders as shown in Figure 1.13 and a highly (0.001) significant effect for the treatments. Hence the data given in Figures 1.14 and 1.15 represent the mean pressures from both plates and cylinders.

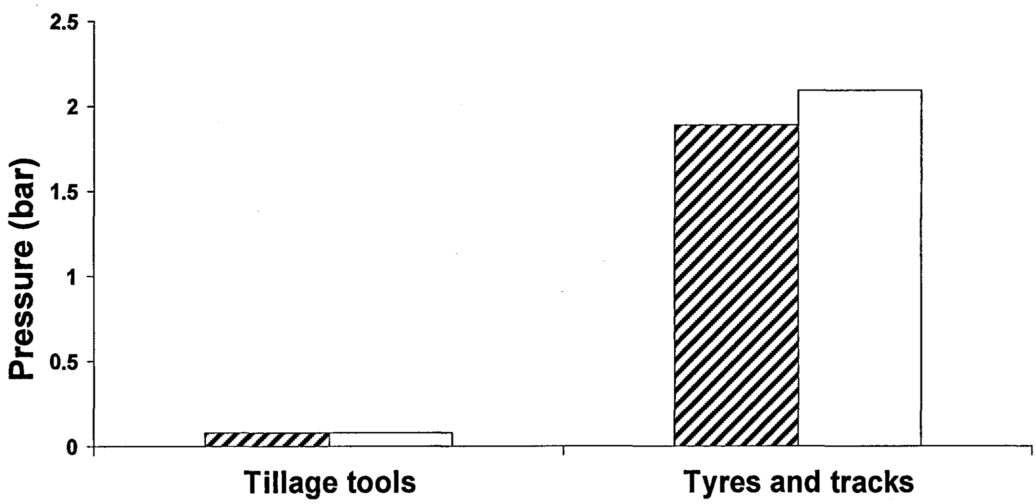


Figure 1.13. Comparison of overall mean pressure recorded by the cylinder (hatched) and plate (clear) sensors with LSDs of 0.058 and 0.86 respectively at the 95% confidence limit.

3.1.4 The peak pressures recorded by the implement loads at 250 mm are shown in Figure 1.14. Unsurprisingly the largest pressure (*c* 0.30 bar) recorded was that of a furrow press, followed by a heavy roller and DD rings. The chisel tines, mouldboard plough and root harvester share all had pressures higher than a human walking over the surface (which produced a peak pressure of 0.03 bar) and the remaining tillage implement pressures were less, with the shallow mouldboard plough at 0.007 bar.

3.1.5 All of the tyre/track loads, given in Figure 1.15, produced greater peak pressures than the tillage implements, ranging from 0.4 bar to 6.6 bar, depending on load, inflation pressure and carcass stiffness. As expected, the greatest pressure resulted from a truck/trailer tyre inflated to 7 bar, carrying a load of 5 t. This was significantly more than that of a 10 t harvester tyre inflated to either 1 or 2 bar pressure. All soil pressures were substantially greater than a human walking.

3.1.6 The overall benefits of reduction in tyre inflation pressure and load are evident from comparing either high/low pressure for the same load or high/low load for the same pressure. There is also clear benefit from equipping field going machines with either dual tyres or rubber tracks in comparison with a single tyre.

3.1.7 Namely that:

- reducing the inflation pressure from 2 to 1 bar at a constant load of 10 t and 2 t for harvester and tractor tyres respectively reduces the soil pressure at 250 mm deep by 26% and 37%

- reducing the load of the harvester tyre from 10 t to 5 t at a constant inflation pressure of 2 bar reduces the soil pressure at 250 mm by 56%
- the use of dual tyres which reduces the load per tyre whilst maintaining inflation pressure results in a 42% reduction in soil pressure and with a 50% reduction in inflation pressure (which may be possible in certain circumstances) results in a 63% reduction in soil pressure at 250 mm deep
- the data for the rubber tracks in comparison with the harvester tyres show a significant (52%) reduction in soil pressure even when the extra weight of the track is considered. These results are supported by the findings of Ansorge and Godwin (2007; 2008). In the latter studies these authors showed that a 32 t rubber tracked combine harvester produced a similar soil deformation profile and compaction to a 10 t combine on the tyres sizes recommended in the 1970s.

3.1.8 Whilst many of the above one to one relationships are expected, the unique feature of this data set is that it compares a range of ground drive equipment under controlled conditions and enables comparisons to be made between alternative systems. This will then provide a definitive data set indicating those implements and tyre/track systems that cause damage to buried archaeological material once the threshold pressures for artefact damage have been identified.

3.1.9 Figure 1.16 shows the effect of multiple passes for four of the wheel/tyre configurations and illustrates that the peak pressures tend to rise above that of the first pass by a small amount (*c* 10%) and then remain constant.

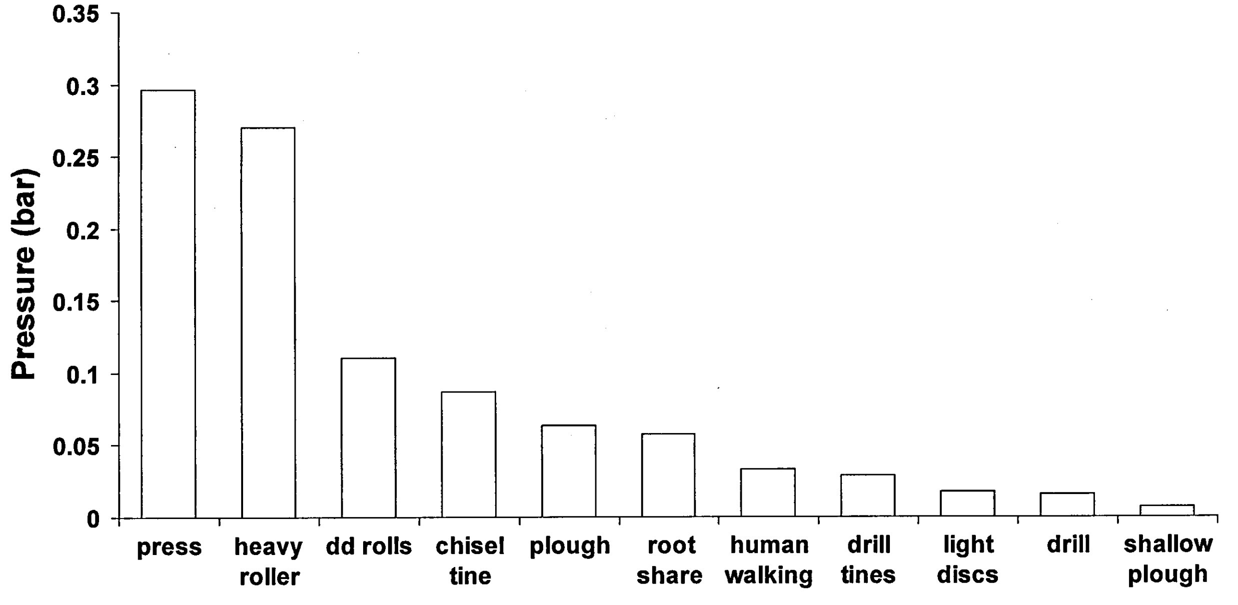


Figure 1.14. Mean implement peak pressures at 250 mm depth. The LSD at the 95% confidence interval was 0.058.

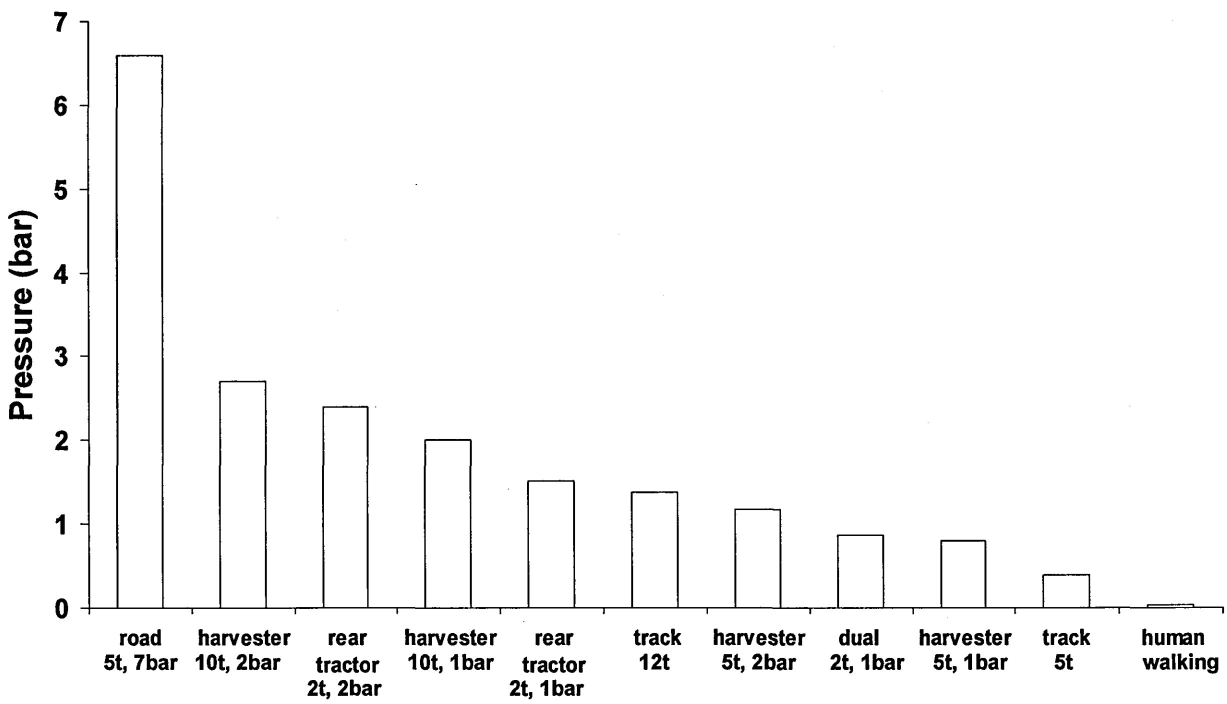


Figure 1.15. Mean tyre/track peak pressures at 250 mm depth.. The LSD at the 95% confidence interval was 0.74.

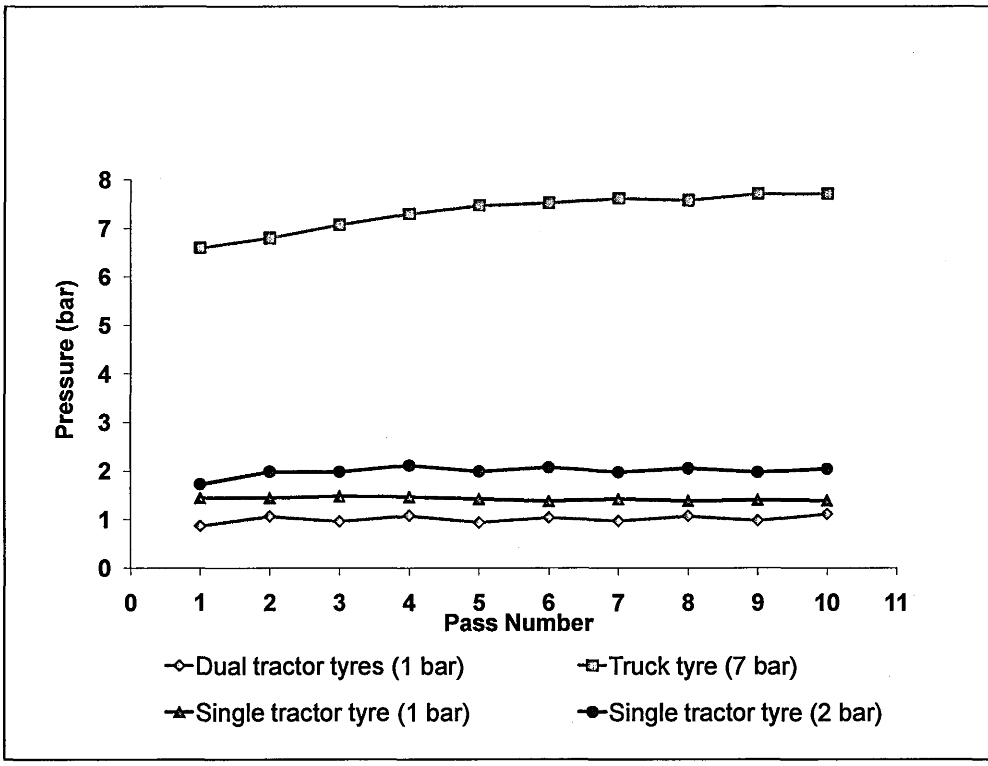


Figure 1.16. The effect of number of passes on the recorded pressure at 250 mm depth.

3.1.10 The effect of depth on transmission of surface applied loads from a number of implements and wheel systems can clearly be seen from Figures 1.17 and 1.18. Figure 1.17 also shows the data from the shallower sensors placed nominally 25 mm below the depth of the shallower tillage tools, eg the chisel tines. Also given is the pressure (0.17 bar) at a depth of 425 mm caused by the passage of a subsoiler tine operating at 400 mm. This, unexpectedly, is virtually the same pressure (0.18 bar) as that below a chisel tine at the similar depth of separation between the tine tip and the sensors. Unfortunately, there was a repeated problem with the sensor at a depth of 400 mm and hence the data from this are not shown, but this is not a significant problem as there were sensors at 350 mm.

3.1.11 The results in Figure 1.18 support the findings of Soehne (1958) that the pressure decreases with depth. They also clearly demonstrate the effect of the high inflation pressure road tyre compared to the other agricultural tyres and tracks. The road tyre produces a resulting soil pressure of approximately 1 bar at 650 mm depth; all other systems exhibit pressures less than 1 bar at depths of 400 mm and deeper, falling to 0.5 bar and less at 650 mm. Small increases in pressure at a depth of 350 mm over those recorded at 250 mm could be due to the effect of tyre lugs as there was no practical method to synchronise the data so that either a lug or inter-lug always coincided with the sensors. These differences were no greater than the LSD at the 95% probability level of the data from the replicated sensors at a depth of 250 mm.

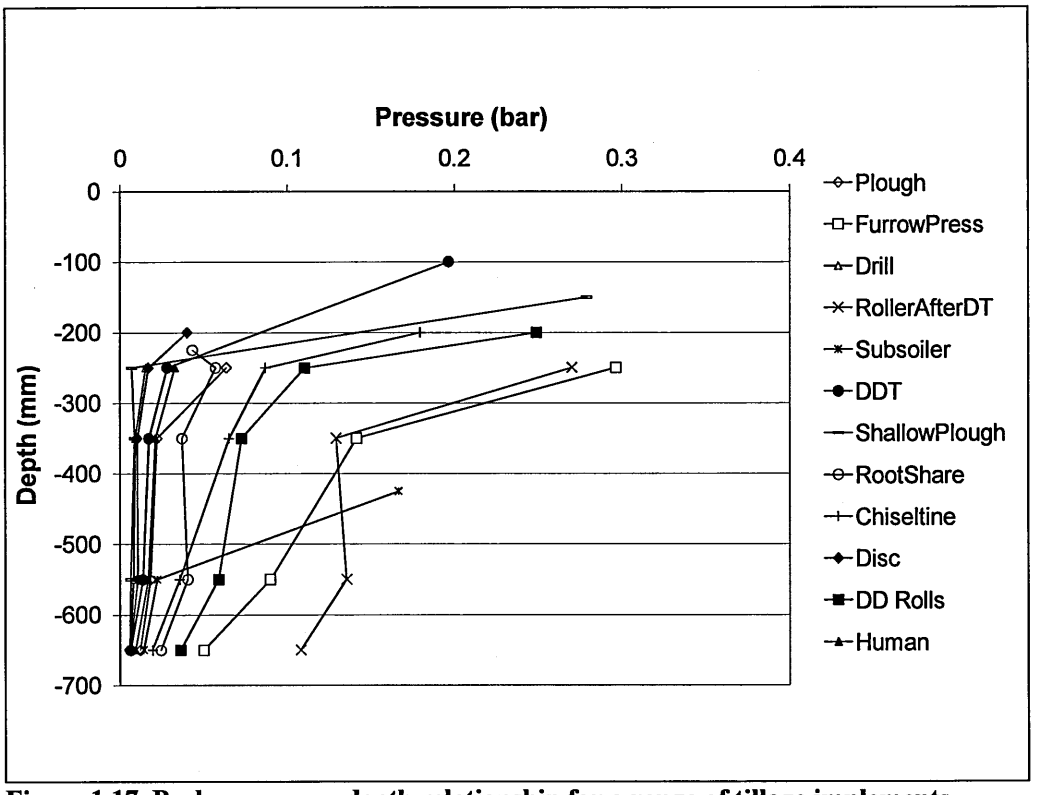


Figure 1.17. Peak pressure v depth relationship for a range of tillage implements. The LSD at 250 mm at the 95% confidence interval was 0.058.

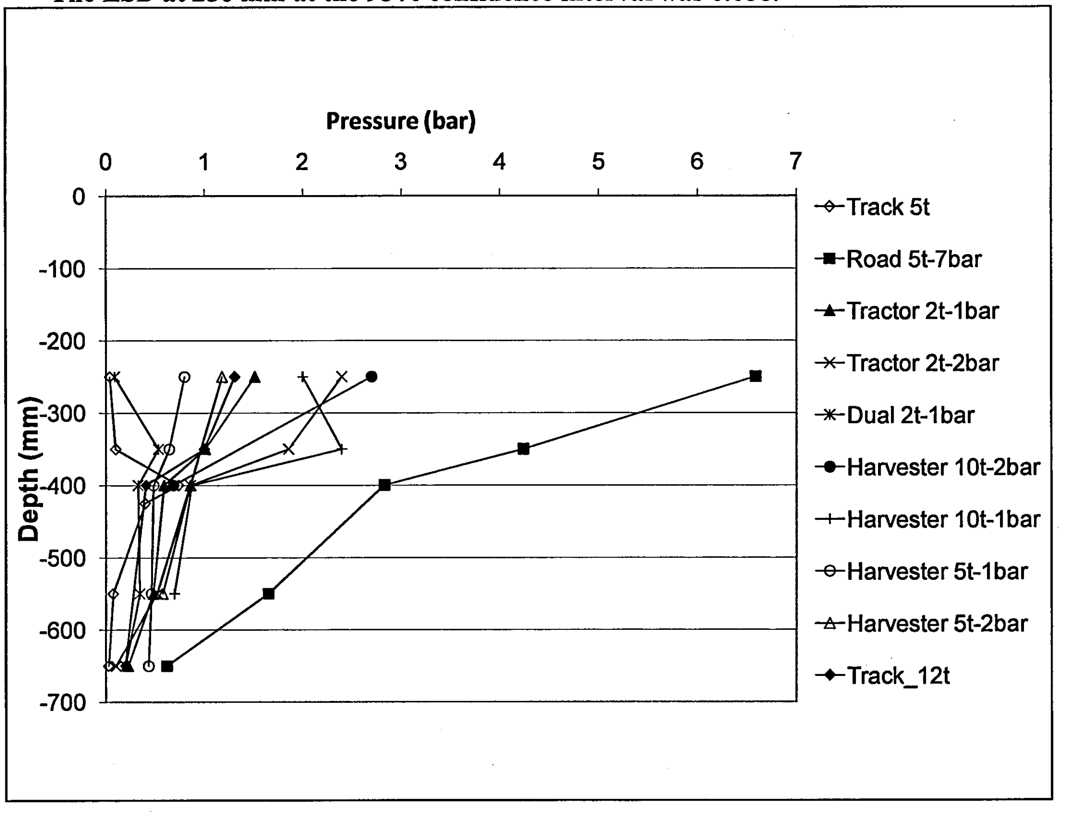


Figure 1.18. Peak pressure v depth relationship for a range of tyre and track loads. The LSD at 250 mm at the 95% confidence interval was 0.74.

3.2 Field studies in clay soil

3.2.1 Figure 1.19 shows typical data from the MF390 tractor followed by a tandem axle trailer; it is interesting to note that the rear tractor and the rear trailer tyres produce virtually the same peak pressure at 0.44 bar.

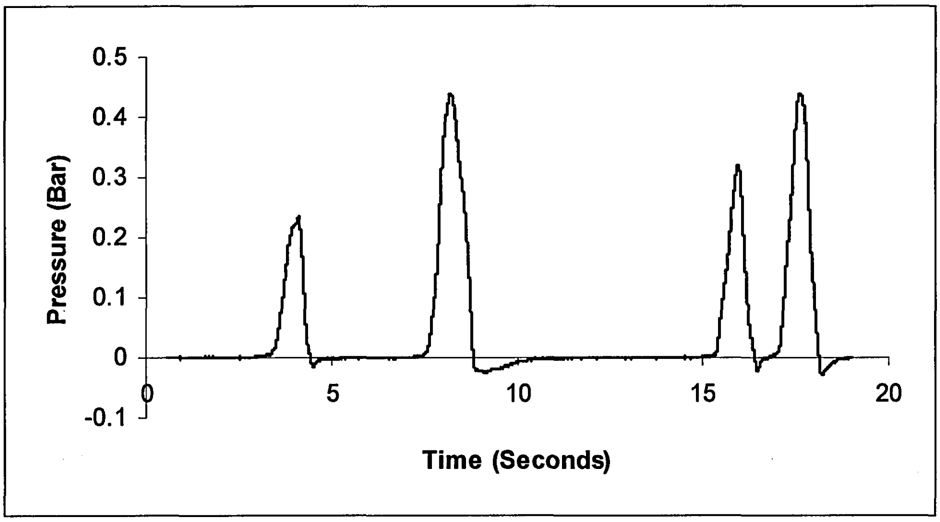


Figure 1.19. Pressure readings from 400 mm deep cylindrical sensor showing the effect of (from left to right) the front and rear axles of the tractor followed by the twin tyres of the tandem axle trailer.

3.2.2 The reported pressures in Table 1.3 show the peak pressures (bar) recorded on the cylindrical sensors in the clay field. The data show that a number of sensors failed during the period that they remained in the soil, namely:

- Replicate 1 at both 300 and 400 mm depth
- Replicate 2 at 500 mm and
- Replicate 3 at 600 mm

3.2.3 This is unfortunate in that it makes any statistical analysis meaningless. The other complicating factor is that the pressures recorded at 300 mm are often the lowest rather than the highest in the vertical profile. This was attributed to shrinkage of the clay packing in the augured holes as a result of drying over the summer period, leaving the sensor without contact with the stronger (through drying) overlying soil.

3.2.4 However it is possible to arrive at some conclusions, namely that for the September study:

- the peak pressures generally reduce with depth, as shown for the laboratory data in Figure 1.18
- the peak pressures generally increase with the severity of the expected loading, in that pressures under the human are between 0.00 and 0.01 bar, increasing to 0.04-0.08 bar under the terra tyre, up to 0.09 bar under the single tractor tyre, to

0.16-0.38 bar under the Fendt tractor and raised subsoiler and up to 0.44 bar below the MF390 tractor pulling the trailer
- the values at 400 to 500 mm deep are marginally less than those in the sandy soil in the laboratory study (shown in Figure 1.18). This would be expected because the field soil was "virtually undisturbed" clay which will have greater strength than the laboratory sandy loam soil which was disturbed and re-compacted for each test

3.2.5 The analysis of the May data shows:

- peak pressures with similar orders of magnitude and characteristics to those of the September data
- that the tracked combine at 32 tonnes in May produced a lower peak pressure than that of the Fendt tractor with a raised subsoiler at 8 tonnes during the previous September

Table 1.3. Peak pressure (bar) of the field study on clay soil.

Load type	Sensor depth, mm	Rep.1 Sept	Rep.1 May	Rep.2 Sept	Rep.2 May	Rep.3 Sept	Rep.3 May
Human walking	300	-	-	0.00	0.013	0.00	0.00
	400	-	-	0.01	0.07	0.00	0.00
	500	0.00	0.01	-	-	0.00	0.08
	600	0.00	0.01	0.00	0.01	-	-
Terra tyre	300	-	-	0.01	0.00	0.00	0.01
	400	-	-	0.11	0.07	0.00	0.10
	500	0.04	0.08	-	-	0.08	0.03
	600	0.01	0.02	0.00	0.02	-	-
Dual tyres	300	-	-	0.00	0.35	0.01	0.01
	400	-	-	0.12	0.11	0.06	0.03
	500	0.02	0.05	-	-	0.00	0.01
	600	0.00	0.02	0.00	0.01	-	-
Pick-up truck	300	-	-	0.01	0.01	0.00	0.01
	400	-	-	0.07	0.14	0.01	0.04
	500	0.00	0.02	-	-	0.01	0.02
	600	0.00	0.01	0.00	-	-	-
Single tractor tyre	300	-	-	0.04	0.04	0.01	0.01
	400	-	-	0.09	0.12	0.09	0.04
	500	0.01	0.07	-	-	0.1	0.01
	600	0.00	0.06	0.00	0.00	-	-
Tractor + Subsoiler	300	-		0.11		0.04	
	400			0.16		0.38	
	500		0.03	-		0.03	
	600		0.09	0.00		-	
Tracked combine	300	-			0.04		0.01
	400	-			0.04		0.07
	500	0.05			-		0.04
	600	0.01			0.06		-
Tractor + Trailer	300	-	-	0.0	0.05	0.14	0.01
	400	-	-	0.12	-	0.44	0.03
	500	0.06	0.32	-	-	0.05	0.03
	600	0.02	0.08	0.00	0.05	-	-

4 DISCUSSION

4.1.1 The evidence presented demonstrates that the effect of tillage implements on pressure transmission to buried objects is very small in comparison to that of the tyre/wheels of trucks, tractors, trailers and harvesters, which were found to be two orders of magnitude greater. Hence, any further work, such as the studies undertaken in the clay field, can be focused on these rather than on tillage implements. Tillage tools will, however, cause fracture of buried archaeological material upon direct impact, and for that reason all the pressure measurements were conducted at depths below which deep mouldboard ploughing (250-300 mm) would have previously caused damage. The impact damage effects of subsoiling and mole ploughing to depths of between 400-600 mm, which are less frequent and generally wider spaced operations, were also outside the remit of this work.

4.1.2 It is evident from this work that an increase in tyre size and corresponding reduction in tyre inflation pressure reduces both the depth and severity of pressure transmission to buried objects through the soil profile. It is pressure rather than axle loads that has the primary effect. There are very important benefits from keeping the load per tyre to a minimum by using dual tyres or multi axles. The use of rubber tracks as an alternative to tyres will reduce the soil pressure under heavily loaded vehicles by a factor of two at a depth of 250 mm.

4.1.3 There was no overall significant difference between the pressures recorded by the cylinder and the wall mounted sensors and as a result, for convenience of installation, the cylinders were used in the clay field studies.

4.1.4 It is unfortunate that the shallower sensors failed in the clay field experiment, but it is interesting to note that the deeper sensors in this relatively undisturbed soil reported pressures that were marginally less than those in the disturbed sandy loam soil in the laboratory. Hence, the laboratory results can be considered a worst case scenario and using them for further analysis would give an extra margin of safety in any recommendations.

4.1.5 As a result of the weaknesses in the field data one cannot draw definitive conclusions about the effects of the difference in soil conditions between September and May, as there is little evidence to suggest that the soil pressures recorded at depths of 400 mm and greater are different.

4.1.6 If similar field experiments were to be repeated it is recommended that the recording of surface traffic should take place within days of the installation of the sensors.

4.1.7 The unique feature of this data set is that it compares the effects of a range of ground drive equipment under controlled conditions and enables comparisons to be made between alternative systems. This will then be a definitive data set indicating those implements and tyre/track systems that cause damage to buried archaeological material once the threshold pressures have been identified.

4.1.8 The validity of the results is discussed in Appendix 3 (section 8) in relation to their applicability to the field results.

5 CONCLUSIONS

5.1.1 The effect caused by wheeled and track loads, on the transmission of pressure to buried objects, is two orders of magnitude greater than that of tillage implements.

5.1.2 The truck tyre loaded to 5 t and inflated to 7 bar is the most damaging of all the applied loads. This is followed at less than half the subsoil pressure by a combine harvester tyre loaded to 10 t but inflated to 2 bar; a further reduction in this tyre pressure to 1 bar produces a still further (26%) reduction in subsoil pressure. This and other comparisons with the same load at two pressures illustrate the importance of reducing tyre pressure to the lowest safe working inflation pressure commensurate with vehicle stability and not inflicting damage to the tyre carcass.

5.1.3 A reduction in tyre inflation pressure and an increase in tyre size may reduce both the depth and severity of pressure transmission to buried objects.

5.1.4 The use of dual tyres/wheels and rubber tracks has a very significant effect in reducing soil pressure at depth.

5.1.5 The recorded pressure reduces significantly with depth: the pressure from the truck tyre with an inflation pressure of 7 bar is at approximately 1 bar at a depth of 650 mm.

5.1.6 Multiple passes of wheels/tyres can cause an approximate increase of 10% in subsoil pressure over that caused by the first pass.

5.1.7 Not surprisingly, the largest resulting soil pressure from the tillage implements resulted from the furrow press (0.30 bar) and the heavy roller (0.27 bar) and the DD rolls (0.11 bar). All other pressure were less than 0.1 bar.

5.1.8 There was no significant difference between the pressures recorded by the cylinder and wall-mounted sensors. Hence, the cylinder sensor was used in the clay field studies.

5.1.9 The pressure transmission to buried objects from wheel and track loads is marginally less in clay soil than in sandy soils at depths of greater than 400 mm. This was ascribed to the potentially greater undisturbed strength of the clay soil.

5.1.10 Over the range considered the soil moisture conditions had limited effect on the pressures transmitted in sand or clay soils.

5.1.11 The above data enable identification of those operations in which archaeological damage could occur once the threshold values have been identified in later appendices of this report.

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Appendix G: Field specifications

SEE FOLLOWING TWO PAGES

YEARS 1-5	September 12 - 13 2006	Midpoint of Moisture Content Range = 12.5					
Implement	**Tractor**	**Depth**	**Weight**	**Front Tyre**	**Pressure (bar)**	**Back Tyre**	**Pressure (bar)**
Plough	Massey Ferguson 6180 4wd	250	5420	380/70 R28	1	480/70 R38	0.5
	Plough 4-share reversible		980				
Shallow Plough	Massey Ferguson 230 2wd	125	1700	6.00-16	2	12.4/11-28	1.5
	Shallow plough 2-share non-reversible		200				
Simba Solo	Fendt 930 4wd	125	8300	600/65 R36	1.2	650/85 R38	1.2
	Solo 380		6900				
Subsoil	Fendt 930 4wd	400	8300	600/65 R38	1.2	650/85 R40	1.2
	Cousins Vform 5-tine subsoiler		2000				
Direct Drill	Fendt 930 4wd	75	8300	600/65 R37	1.2	650/85 R39	1.2
	Vaderstad Rapid 300 Super XL with System Disc		3400				
Roll	Ford 5640 2wd		3300	400-17.5	0.7	66x43.0-25	0.6
	Cambridge Rolls		3000				
Spray 1	Spray Coupe 4440 with 1200 L water		6000	12.4-24 12 ply	1.2	12.4-24 12 ply	1.2
Spray 2	Spray Coupe 4440 with 1200 L water		6000	12.4-24 12 ply	1.2	12.4-24 12 ply	1.2
Harvester	Challenger MT765B Rubber tracked tractor		15000		2438mm x 760mm (25" wide belts)		
Tractor-Trailer Combo	Ford 7810 4wd		4384	13.6-28	1.25	16.4-34	1.25
	Massey Ferguson 700 trailer		3352	12.5/80 x 15.3	2.5	12.5/80 x 15.3	2.5
	Trailer loaded		8600				

YEARS 5-8	October 16 - 18 2006	Midpoint of Moisture Content Range = 26.0					
Implement	**Tractor**	**Depth**	**Weight**	**Front Tyre**	**Pressure (bar)**	**Back Tyre**	**Pressure (bar)**
Plough	Massey Ferguson 6180 4wd	250	5420	380/70 R28	1	480/70 R38	0.5
	Plough 4-share reversible		980				
Shallow Plough	Massey Ferguson 230 2wd	125	1700	6.00-16	2	12.4/11-28	1.5
	Shallow plough 2-share non-reversible		200				
Simba Solo	Fent 818 4wd	125	8000	540/65 R30	1.1	650/65 R42	1.2
	Solo 330 ST		6250				
Subsoil	Fent 818 4wd	400	8000	540/65 R30	1.1	650/65 R42	1.2
	Cousins Vform 5-tine subsoiler		2000				
Direct Drill	Fent 818 4wd	75	8000	540/65 R30	1.1	650/65 R42	1.2
	Vaderstad Rapid 300 Super XL with System Disc		3400				
Roll	Ford 5640 2wd		3300	400-17.5	0.7	66x43.0-25	0.6
	Cambridge Rolls		3000				
Spray 1	Spray Coupe 4440 with 1200 L water		6000	12.4-24 12 ply	1.2	12.4-24 12 ply	1.2
Spray 2	Spray Coupe 4440 with 1200 L water		6000	12.4-24 12 ply	1.2	12.4-24 12 ply	1.2
Harvester	Challenger MT765B Rubber Tracked Tractor		15000		2438mm x 760mm (25" wide belts)		
Tractor-Trailer Combo	Ford 7810 4wd		4384	13.6-28	1.25	16.4-34	1.25
	Massey Ferguson 700 trailer		3352	12.5/80 x 15.3	2.5	12.5/80 x 15.3	2.5
	Trailer loaded		5820				

YEARS 8-15	May 21 - 24 2007	Midpoint of Moisture Content Range = 19.5					
Implement	**Tractor**	**Depth**	**Weight**	**Front Tyre**	**Pressure (bar)**	**Back Tyre**	**Pressure (bar)**
Plough	Massey Ferguson 6180 4wd	250	5420	380/70 R28	1	480/70 R38	0.5
	Plough 4-share reversible		980				
Shallow Plough	Massey Ferguson 230 2wd	125	1700	6.00-16	2	12.4/11-28	1.5
	Shallow plough 2-share non-reversible		200				
Simba Solo	Challenger MT765B Rubber Tracked Tractor	125	15000		2438mm x 760mm (25" wide belts)		
	Solo 330 ST		6250				
Subsoil	New Holland TM 190 4wd	400	7924	540/65 R30	1.25	650/65 R42	1.25
	Cousins Vform 5-tine subsoiler		2000				
Direct Drill	New Holland TM 190 4wd	75	7924	540/65 R30	1.25	650/65 R42	1.25
	Vaderstad Rapid 300 Super XL with System Disc		3400				
Roll	Ford 5640 2wd		3300	400-17.5	0.7	66x43.0-25	0.6
	Cambridge Rolls		3000				
Spray 1	Spray Coupe 4440 with 1200 L water		6000	12.4-24 12 ply	1.2	12.4-24 12 ply	1.2
Spray 2	Spray Coupe 4440 with 1200 L water		6000	12.4-24 12 ply	1.2	12.4-24 12 ply	1.2
Harvester	Challenger MT765B Rubber Tracked Tractor		15000		2438mm x 760mm (25" wide belts)		
Tractor-Trailer Combo	Massey Ferguson 390 4wd		3763	7.5-16 8 ply	1	13.6 R38 6 ply	1.2
	Massey Ferguson 700 trailer		3352	12.5/80 x 15.3	2.5	12.5/80 x 15.3	2.5
	Trailer loaded		7052				

YEARS 15-20 **October 4 - 8 2007** **Midpoint of Moisture Content Range = 13.5**

Implement	Tractor	Depth	Weight	Front Tyre	Pressure (bar)	Back Tyre	Pressure (bar)
Plough	Massey Ferguson 6180 4wd	250	5420	380/70 R28	1	480/70 R38	0.5
	Plough 4-share reversible		980				
Shallow Plough	Massey Ferguson 230 2wd	125	1700	6.00-16	2	12.4/11-28	1.5
	Shallow plough 2-share non-reversible		200				
Simba Solo	Fent 718 4wd	125	6985	540/65 R28	1	650/65 R38	1
	or Claas Area 830 4wd		6750	540/65 R30	1	650/85 R42	1
	Solo 330 ST		6250				
Subsoil	Fent 718 4wd	400	6985	540/65 R28	1	650/65 R38	1
	Cousins Vform 5-tine subsoiler		2000				
Direct Drill	Fent 718 4wd	75	6985	540/65 R28	1	650/65 R38	1
	Moore Unidrill Direct Drill		3500				
Roll	Ford 5640 2wd		3300	400-17.5	0.7	66x43.0-25	0.6
	Cambridge Rolls		3000				
Spray 1	Spray Coupe 4440 with 1200 L water		6000	12.4-24 12 ply	1.2	12.4-24 12 ply	1.2
Spray 2	Spray Coupe 4440 with 1200 L water		6000	12.4-24 12 ply	1.2	12.4-24 12 ply	1.2
Harvester	Fent 718 with Subsoiler		6985	540/65 R28	1	650/65 R38	1
	or Claas Ares 830 4wd with Subsoiler		6750	540/65 R30	1	650/85 R42	1
	Cousins Vform 5-tine subsoiler		2000				
Tractor-Trailer Combo	Massey Ferguson 390 4wd		3763	7.5-16 8 ply	1	13.6 R38 6 ply	1.2
	Massey Ferguson 700 trailer		3352	12.5/80 x 15.3	2.5	12.5/80 x 15.3	2.5
	Trailer loaded		7052				

YEARS 20-25 **April 21 - 22 2008** **Midpoint of Moisture Content Range = 22.5**

Implement	Tractor	Depth	Weight	Front Tyre	Pressure (bar)	Back Tyre	Pressure (bar)
Plough	Massey Ferguson 6180 4wd	250	5420	380/70 R28	1	480/70 R38	0.5
	Plough 4-share reversible		980				
Shallow Plough	Massey Ferguson 230 2wd	125	1700	6.00-16	2	12.4/11-28	1.5
	Shallow plough 2-share non-reversible		200				
Simba Solo	Claas Ares 836RZ 4wd	125	9470	16.9R30	1.25	20.8R42	1.25
	Simba Solo X-Press 4.6m		5542				
Subsoil	Fendt 820 Vario 4wd	400	7185	540/65 R30	1.25	650/65 R42	1.25
	Cousins Vform 5-tine subsoiler		2000				
Direct Drill	Claas Ares 836RZ 4wd	75	7940	16.9R30	1.25	20.8R42	1.25
	Moore Unidrill Direct Drill		3500				
Roll	Ford 5640 2wd		3300	400-17.5	0.7	66x43.0-25	0.6
	Cambridge Rolls		3000				
Spray 1	Spray Coupe 4440 with 1200 L water		6000	12.4-24 12 ply	1.2	12.4-24 12 ply	1.2
Spray 2	Spray Coupe 4440 with 1200 L water		6000	12.4-24 12 ply	1.2	12.4-24 12 ply	1.2
Harvester	Claas 580TT Combine Harvester Tracked		20200	width 630 mm	Terra Tracks	600/55-29.5	1.9
	w/ Conspeed eight row Maize Header		23400				
	or w/ Vario 900 Header		23100				
Tractor-Trailer Combo	Massey Ferguson 390 4wd		3763	7.5-16 8 ply	1	13.6 R38 6 ply	1.2
	Massey Ferguson 700 trailer		3352	12.5/80 x 15.3	2.5	12.5/80 x 15.3	2.5
	Trailer loaded		7740				

YEARS 25-30 **May 14 - 20 2008** **Midpoint of Moisture Content Range = 19.5**

Implement	Tractor	Depth	Weight	Front Tyre	Pressure (bar)	Back Tyre	Pressure (bar)
Plough	Massey Ferguson 6180 4wd	250	5420	380/70 R28	1	480/70 R38	0.5
	Plough 4-share reversible		980				
Shallow Plough	Massey Ferguson 230 2wd	125	1700	6.00-16	2	12.4/11-28	1.5
	Shallow plough 2-share non-reversible		200				
Simba Solo	Claas Ares 836RZ 4wd	125	9470	16.9R30	1.25	20.8R42	1.25
	Simba Solo X-Press 4.6m		5542				
Subsoil	Fendt 820 Vario 4wd	400	7185	540/65 R30	1.25	650/65 R42	1.25
	Cousins Vform 5-tine subsoiler		2000				
Direct Drill	Fendt 820 Vario 4wd	75	7185	540/65 R30	1.25	650/65 R42	1.25
	or: Claas Ares 836RZ 4wd		7940	16.9R30	1.25	20.8R42	1.25
	Moore Unidrill Implement (Direct Drill)		3500				
Roll	Ford 5640 2wd		3300	400-17.5	0.7	66x43.0-25	0.6
	Cambridge Rolls		3000				
Spray 1	Spray Coupe 4440 with 1200 L water		6000	12.4-24 12 ply	1.2	12.4-24 12 ply	1.2
Spray 2	Spray Coupe 4440 with 1200 L water		6000	12.4-24 12 ply	1.2	12.4-24 12 ply	1.2
Harvester	Claas 580TT Combine Harvester Tracked		20200	width 630 mm	Terra Tracks	600/55-29.5	1.9
	w/ Conspeed eight row Maize Header		23400				
	or w/ Vario 900 Header		23100				
Tractor-Trailer Combo	Massey Ferguson 390 4wd		3763	7.5-16 8 ply	1	13.6 R38 6 ply	1.2
	Massey Ferguson 700 trailer		3352	12.5/80 x 15.3	2.5	12.5/80 x 15.3	2.5
	Trailer loaded		7740				

Appendix H: Statistical analysis – Field pressure values

The following is the program output from GenStat for the Unbalanced Analysis of Variance performed on the field pressure data.

H.1 Field pressure values – Input instructions for analysis and statistical output

- " Unbalanced Analysis of Variance "
- BLOCK "No blocking"
- TREATMENT plot+operation
- COVARIATE Moisture_Midpoint
- DELETE [REDEFINE=yes] _ausave
- AUNBALANCED [PRINT=aovtable,means,screen; PSE=diff,lsd,means; LSDLEVEL=5; COMBINATIONS=estimable;\
- ADJUSTMENT=marginal; FACT=3; FPROB=yes] Peak_Pressures; SAVE=_ausave

Screening of terms in an unbalanced design

Variate: Peak_Pressures

Marginal and conditional test statistics and degrees of freedom

degrees of freedom for denominator (full model): 673

term	mtest	mdf	ctest	cdf
plot	9.24	3	9.54	3
operation	31.13	10	31.23	10

P-values of marginal and conditional tests

term	mprob	cprob
plot	0.000	0.000
operation	0.000	0.000

Analysis of an unbalanced design using GenStat regression

Variate: Peak_Pressures

Accumulated analysis of variance

Change	d.f.	s.s.	m.s.	v.r.	F pr.
+ Moisture_Midpoint	1	0.0033	0.0033	0.02	0.886
+ plot	3	4.4658	1.4886	9.24	<.001
+ operation	10	50.3004	5.0300	31.23	<.001
Residual	673	108.4134	0.1611		
Total	687	163.1828	0.2375		

Predictions from regression model

The standard errors are appropriate for interpretation of the predictions as summaries of the data rather than as forecasts of new observations.

Response variate: Peak_Pressures

plot	Prediction	se
Inversion	1.304	0.03172
Non-Inversion	1.134	0.03056
Shallow Inversion	1.221	0.03107
Zero Till	1.079	0.03185

Minimum standard error of difference	0.04426
Average standard error of difference	0.04457
Maximum standard error of difference	0.04493
Minimum least significant difference	0.08691
Average least significant difference	0.08751
Maximum least significant difference	0.08822

Predictions from regression model

The standard errors are appropriate for interpretation of the predictions as summaries of the data rather than as forecasts of new observations.

Response variate: Peak_Pressures

operation	Prediction	se
Drill	1.033	0.03863
Harvester	1.295	0.03863
Pigtails	0.430	0.12283
Plough	2.036	0.20272
Roll	0.677	0.04297
Shallow Plough	1.609	0.16607
Simba Solo	1.214	0.07683
Spray 1	1.273	0.03864
Spray 2	1.310	0.03828
Tractor/Trailer	1.463	0.03828
ZigZag	0.467	0.18044

Minimum standard error of difference	0.0541
Average standard error of difference	0.1396
Maximum standard error of difference	0.2710
Minimum least significant difference	0.1063
Average least significant difference	0.2741
Maximum least significant difference	0.5321

Graphic iteration of data

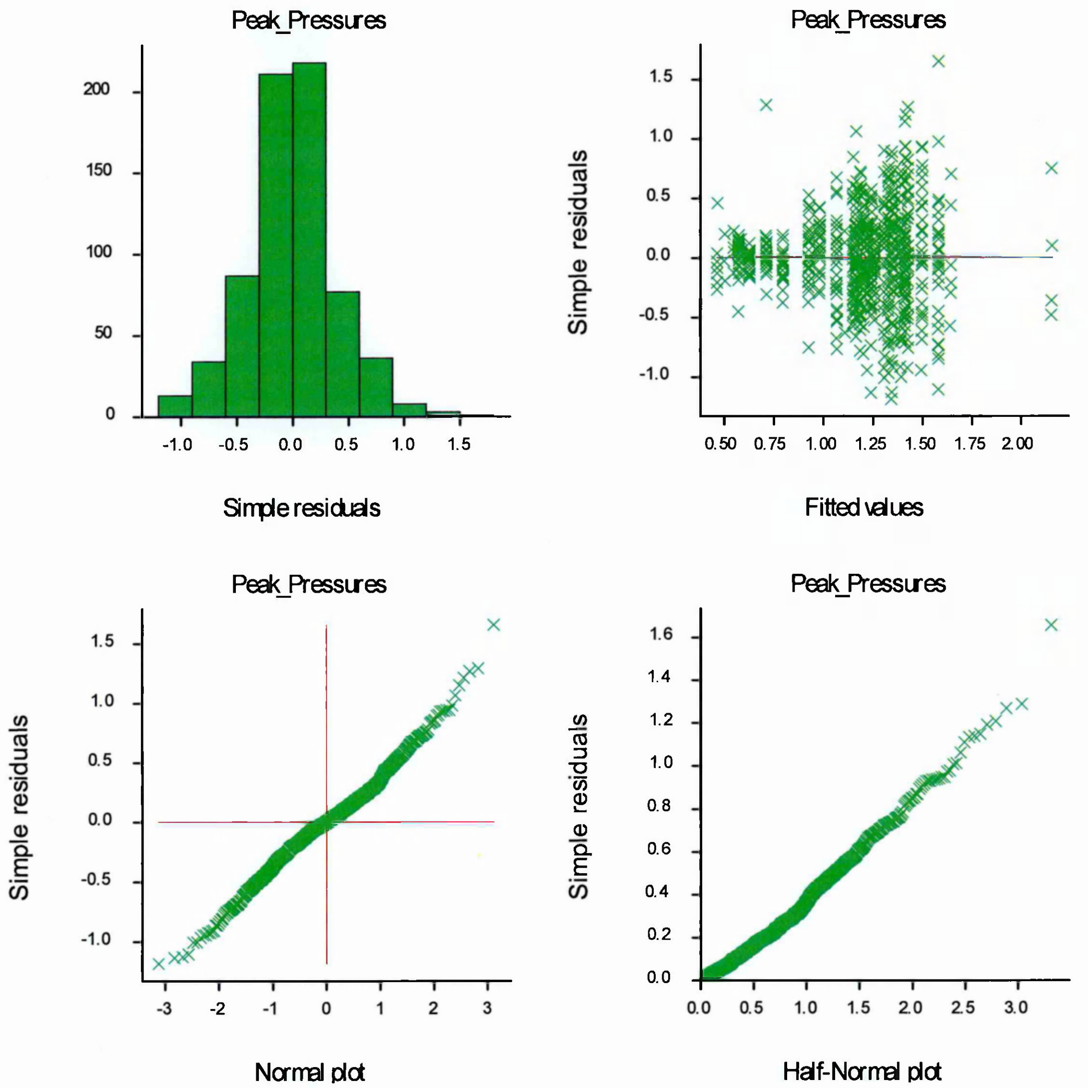


Figure H.1: Residual histogram and scatterplots for analysis of variance of subsurface pressure data collected in the field trials.

Appendix I: Statistical analysis – Laboratory pressure values

The following is the program outputs from GenStat for the Analyses of Variance performed on the subsurface pressure data collected in the soil bin laboratory within the buried object breakage trials.

I.1 Pressure data – Analysis of variance on all four sensors

First analysis of pressure sensor values looked at the outputs of all four pressure sensors used within the laboratory soil bin breakage trials. Here, the four sensors were evaluated against each other regardless of which run the pressures were recorded in and blocking the analysis by trial to exclude the effect any variation between trials might have had on the data.

The four sensors were sensors Z, 13, 18, and 3. The results showed that the output from sensor Z was significantly different the other three, so this sensor was henceforth excluded from use within analysis.

- " Unbalanced Analysis of Variance "
- BLOCK TRIAL
- TREATMENT SENSOR
- COVARIATE "No Covariate"
- DELETE [REDEFINE=yes] _ausave
- AUNBALANCED [PRINT=aovtable,effects,means,screen; PSE=diff,lsd,means; LSDLEVEL=5;\
- COMBINATIONS=estimable; ADJUSTMENT=marginal; FACT=3; FPROB=yes] PRESSURE; SAVE=_ausave

Screening of terms in an unbalanced design

Variate: PRESSURE

Marginal and conditional test statistics and degrees of freedom

degrees of freedom for denominator (full model): 180

term	mtest	mdf	ctest	cdf
SENSOR	40.28	3	40.28	3

P-values of marginal and conditional tests

term	mprob	cprob
SENSOR	0.000	0.000

Analysis of an unbalanced design using GenStat regression

Variate: PRESSURE

Accumulated analysis of variance

Change	d.f.	s.s.	m.s.	v.r.	F pr.
+ TRIAL	4	74.785	18.696	2.97	0.021
+ SENSOR	3	759.937	253.312	40.28	<.001
Residual	180	1131.885	6.288		
Total	187	1966.607	10.517		

Estimates of parameters

Parameter	estimate	s.e.	t(180)
Constant	2.920	0.507	5.75
TRIAL 2	-0.694	0.595	-1.17
TRIAL 3	0.816	0.561	1.45
TRIAL 4	-0.793	0.561	-1.41
TRIAL 5	0.463	0.576	0.80
SENSOR S-18	0.012	0.517	0.02
SENSOR S-3	0.777	0.517	1.50
SENSOR S-Z	4.849	0.517	9.37

Parameters for factors are differences compared with the reference level:

Factor	Reference level
TRIAL	1
SENSOR	S-13

Predictions from regression model

The standard errors are appropriate for interpretation of the predictions as summaries of the data rather than as forecasts of new observations.

Response variate: PRESSURE

SENSOR	Prediction	se
S-13	2.895	0.3658
S-18	2.908	0.3658
S-3	3.672	0.3658
S-Z	7.744	0.3658

Standard error of differences between predicted means 0.5173
Least significant difference (at 5.0%) for predicted means 1.021

Graphic iteration of data

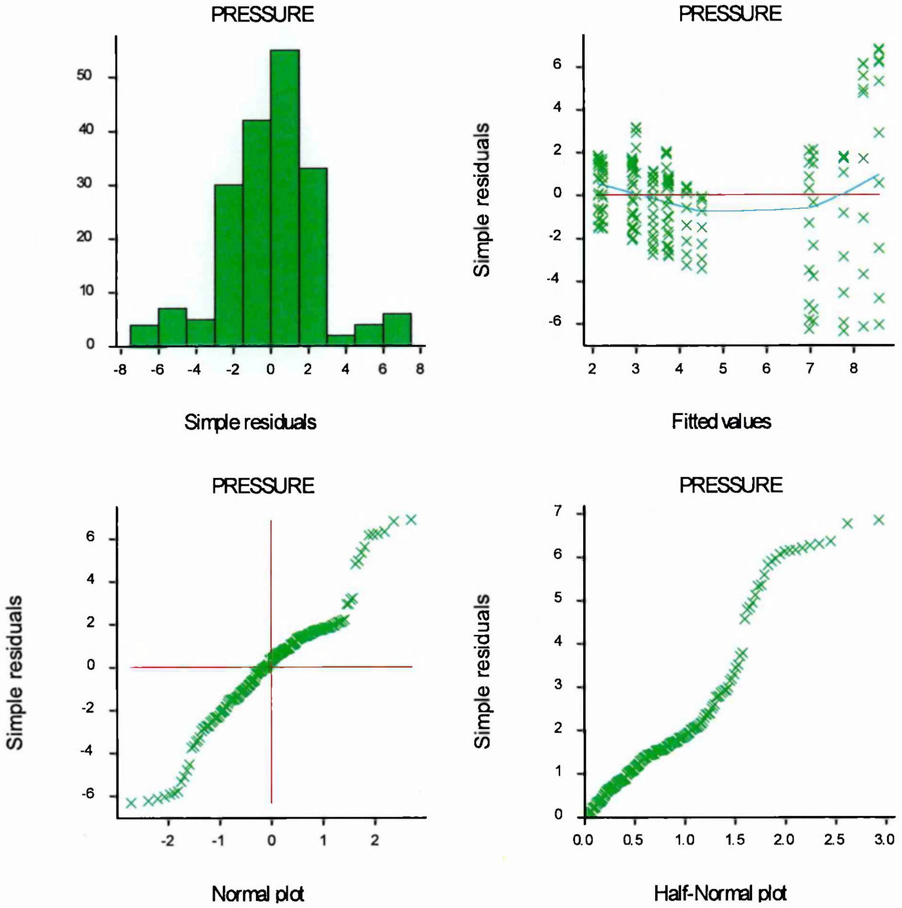


Figure I.1: Residual histogram and scatterplots for analysis of variance of peak pressure data from the four sensors used within the five breakage trials

I.2 Pressure data – Analysis of variance on three remaining sensors

The second analysis of pressure sensor values looked at the outputs of the remaining three pressure sensors used within the laboratory soil bin breakage trials. Here, the three sensors were evaluated against each to see if there was any remaining variation between the sensors. The data was analyzed regardless of which run the pressures were recorded in and blocking the analysis by trial to exclude the effect any variation between trials might have had on the data.

The three remaining sensors were sensors 13, 18, and 3. The results showed that the output from sensor 3 was significantly different the other three, so this sensor was henceforth excluded from use within analysis.

- " Unbalanced Analysis of Variance "
- BLOCK TRIAL_b
- TREATMENT SENSOR_b
- COVARIATE "No Covariate"
- DELETE [REDEFINE=yes] _ausave
- AUNBALANCED [PRINT=aovtable,effects,means,screen; PSE=diff,lsd,alllsd,means; LSDLEVEL=5;\
- COMBINATIONS=estimable; ADJUSTMENT=marginal; FACT=3; FPROB=yes] PRESSURE_b; SAVE=_ausave

Screening of terms in an unbalanced design

Variate: PRESSURE_b

Marginal and conditional test statistics and degrees of freedom

degrees of freedom for denominator (full model): 134

term	mtest	mdf	ctest	cdf
SENSOR_b	4.71	2	4.71	2

P-values of marginal and conditional tests

term	mprob	cprob
SENSOR_b	0.011	0.011

Analysis of an unbalanced design using GenStat regression

Variate: PRESSURE_b

Accumulated analysis of variance

Change	d.f.	s.s.	m.s.	v.r.	F pr.
+ TRIAL_b	4	9.915	2.479	1.26	0.290
+ SENSOR_b	2	18.606	9.303	4.71	0.011
Residual	134	264.413	1.973		
Total	140	292.934	2.092		

Estimates of parameters

Parameter	estimate	s.e.	t(134)
Constant	3.335	0.306	10.89
TRIAL_b 2	-0.597	0.385	-1.55
TRIAL_b 3	-0.317	0.363	-0.88
TRIAL_b 4	-0.703	0.363	-1.94
TRIAL_b 5	-0.632	0.373	-1.69
SENSOR_b S-18	0.012	0.290	0.04
SENSOR_b S-3	0.777	0.290	2.68

Parameters for factors are differences compared with the reference level:

Factor	Reference level
TRIAL_b	1
SENSOR_b	S-13

Predictions from regression model

The standard errors are appropriate for interpretation of the predictions as summaries of the data rather than as forecasts of new observations.

Response variate: PRESSURE_b

SENSOR_b	Prediction	se
S-13	2.895	0.2049
S-18	2.908	0.2049
S-3	3.672	0.2049

Standard error of differences between predicted means 0.2898
Least significant difference (at 5.0%) for predicted means 0.5731

Graphic iteration of data

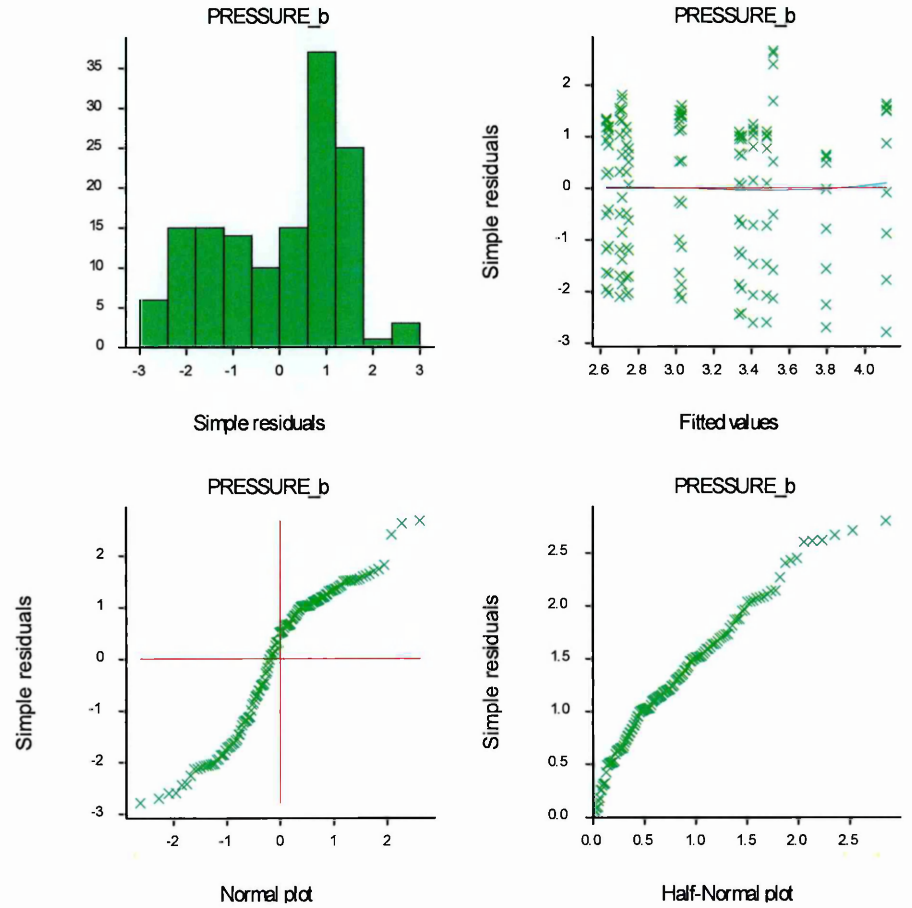


Figure I.2: Residual histogram and scatterplots for analysis of variance of peak pressure data from the three remaining sensors within the five breakage trials

I.3 Pressure data – Analysis of variance on two remaining sensors

The third analysis of pressure sensor values looked at the outputs of the remaining two pressure sensors used within the laboratory soil bin breakage trials. Here, the two sensors were evaluated against each to see if there was any remaining variation. The data was analyzed regardless of which run the pressures were recorded in and blocking the analysis by trial to exclude the effect any variation between trials might have had on the data.

The three remaining sensors were sensors 13, and 18. The results showed that the sensors were not significantly different from each other; thus, their pressure values could therefore be utilized together without differentiation in all analyses for evaluation of object breakage during laboratory trials.

- " Unbalanced Analysis of Variance "
- BLOCK TRIAL_c
- TREATMENT SENSOR_c
- COVARIATE "No Covariate"
- DELETE [REDEFINE=yes] _ausave
- AUNBALANCED [PRINT=aovtable,effects,means,screen; PSE=diff,lsd,alllsd,means; LSDLEVEL=5;\
- COMBINATIONS=estimable; ADJUSTMENT=marginal; FACT=3; FPROB=yes] PRESSURE_c; SAVE=_ausave

Screening of terms in an unbalanced design

Variate: PRESSURE_c

Marginal and conditional test statistics and degrees of freedom

degrees of freedom for denominator (full model): 88

term	mtest	mdf	ctest	cdf
SENSOR_c	0.00	1	0.00	1

P-values of marginal and conditional tests

term	mprob	cprob
SENSOR_c	0.964	0.964

Analysis of an unbalanced design using GenStat regression

Variate: PRESSURE_c

Accumulated analysis of variance

Change	d.f.	s.s.	m.s.	v.r.	F pr.
+ TRIAL_c	4	8.878	2.219	1.29	0.279
+ SENSOR_c	1	0.004	0.004	0.00	0.964
Residual	88	151.014	1.716		
Total	93	159.896	1.719		

Estimates of parameters

Parameter	estimate	s.e.	t(88)
Constant	3.183	0.323	9.87
TRIAL_c 2	-0.797	0.439	-1.81
TRIAL_c 3	0.052	0.414	0.13
TRIAL_c 4	-0.480	0.414	-1.16
TRIAL_c 5	-0.316	0.426	-0.74
SENSOR_c S-18	0.012	0.270	0.05

Parameters for factors are differences compared with the reference level:

Factor	Reference level
TRIAL_c	1
SENSOR_c	S-13

Predictions from regression model

The standard errors are appropriate for interpretation of the predictions as summaries of the data rather than as forecasts of new observations.

Response variate: PRESSURE_c

SENSOR_c	Prediction	se
S-13	2.895	0.1911
S-18	2.908	0.1911

Standard error of differences between predicted means 0.2702
Least significant difference (at 5.0%) for predicted means 0.5370

Graphic iteration of data

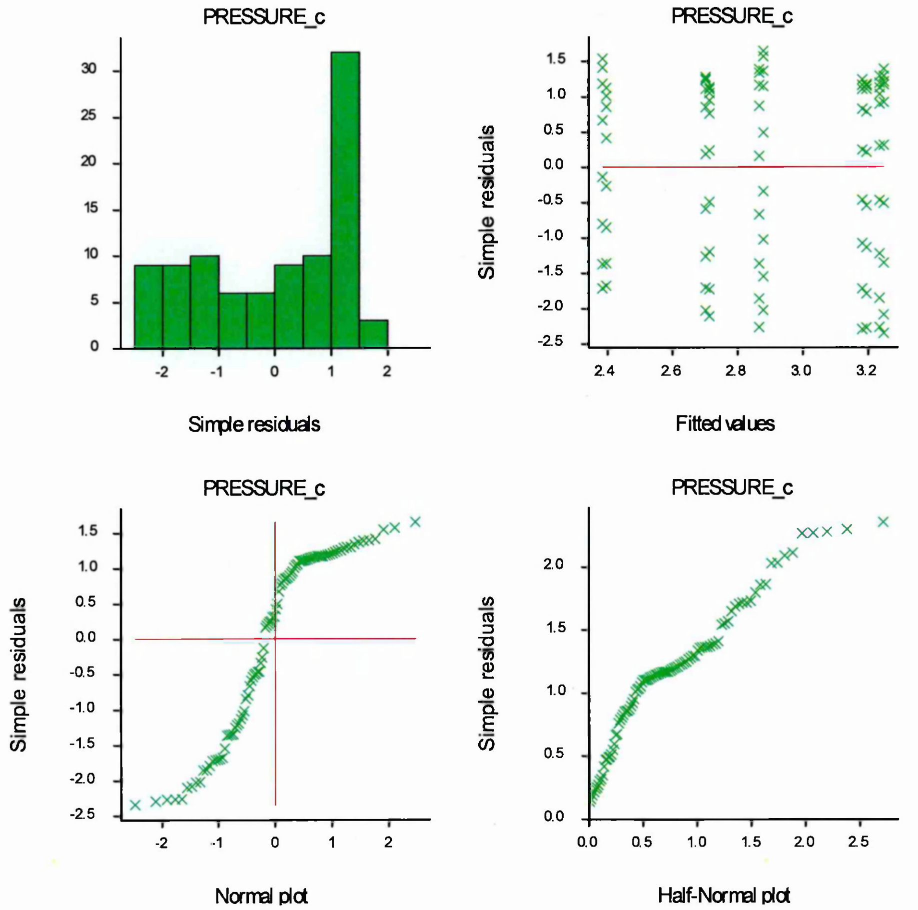


Figure I.3: Residual histogram and scatterplots for analysis of variance of peak pressure data from the two remaining sensors within the five breakage trials

I.4 Pressure data – Analysis of variance of pressures per Trial Run

The fourth analysis of pressure sensor values used the outputs of sensors 13 and 18 to see how the mean peak pressures recorded within the trial varied per trial run. The aim was to find the mean values of peak subsurface pressure for each trial run.

The data was analyzed by blocking the analysis by trial to exclude the effect any variation between trials might have had on the data, and specifying the treatment parameter to be the trial run (the pressure sensors were not differentiated from each other in this analysis).

The results yielded the mean peak subsurface pressure values per run (across all five trials).

- " Unbalanced Analysis of Variance "
- BLOCK TRIAL_d
- TREATMENT RUN_d
- COVARIATE "No Covariate"
- DELETE [REDEFINE=yes] _ausave
- AUNBALANCED [PRINT=aovtable,effects,means,screen; PSE=diff,lsd,alllsd,means; LSDLEVEL=5;\
- COMBINATIONS=estimable; ADJUSTMENT=marginal; FACT=3; FPROB=yes] PRESSURE_d; SAVE=_ausave

Screening of terms in an unbalanced design

Variate: PRESSURE_d

Marginal and conditional test statistics and degrees of freedom

degrees of freedom for denominator (full model): 79

term	mtest	mdf	ctest	cdf
RUN_d	814.09	10	814.09	10

P-values of marginal and conditional tests

term	mprob	cprob
RUN_d	0.000	0.000

Analysis of an unbalanced design using GenStat regression

Variate: PRESSURE_d

Accumulated analysis of variance

Change	d.f.	s.s.	m.s.	v.r.	F pr.
+ TRIAL_d	4	8.87777	2.21944	120.80	<.001
+ RUN_d	10	149.56642	14.95664	814.09	<.001
Residual	79	1.45141	0.01837		
Total	93	159.89560	1.71931		

Estimates of parameter

Parameter	estimate	s.e.	t(79)
Constant	0.9806	0.0518	18.95
TRIAL_d 2	-0.4678	0.0477	-9.80
TRIAL_d 3	0.0713	0.0443	1.61
TRIAL_d 4	-0.4611	0.0443	-10.40
TRIAL_d 5	-0.1592	0.0459	-3.47
RUN_d 2	0.3990	0.0606	6.58
RUN_d 3	0.9724	0.0606	16.04
RUN_d 4	1.6539	0.0606	27.28
RUN_d 5	2.4243	0.0606	39.99
RUN_d 6	3.0112	0.0606	49.68
RUN_d 6.100	3.2272	0.0647	49.88
RUN_d 6.200	3.3404	0.0606	55.11
RUN_d 6.300	3.4324	0.0647	53.02
RUN_d 6.400	3.4318	0.0710	48.32
RUN_d 6.500	3.415	0.109	31.35

Parameters for factors are differences compared with the reference level:

Factor	Reference level
TRIAL_d	1
RUN_d	1

Predictions from regression model

The standard errors are appropriate for interpretation of the predictions as summaries of the data rather than as forecasts of new observations.

Response variate: PRESSURE_d

RUN_d	Prediction	se
1.0	0.788	0.04288
2.0	1.187	0.04288
3.0	1.760	0.04288
4.0	2.441	0.04288
5.0	3.212	0.04288
6.0	3.799	0.04288
6.1	4.015	0.04856
6.2	4.128	0.04288
6.3	4.220	0.04836
6.4	4.219	0.05640
6.5	4.203	0.09999

Minimum standard error of difference	0.06062
Average standard error of difference	0.07262
Maximum standard error of difference	0.11365

Least significant differences (at 5.0%) for predicted means

Rows and columns are labelled by the labels/levels of the factors:

RUN_d 1.0	1	*				
RUN_d 2.0	2	0.1207	*			
RUN_d 3.0	3	0.1207	0.1207	*		
RUN_d 4.0	4	0.1207	0.1207	0.1207	*	
RUN_d 5.0	5	0.1207	0.1207	0.1207	0.1207	*
RUN_d 6.0	6	0.1207	0.1207	0.1207	0.1207	0.1207
RUN_d 6.1	7	0.1288	0.1288	0.1288	0.1288	0.1288
RUN_d 6.2	8	0.1207	0.1207	0.1207	0.1207	0.1207
RUN_d 6.3	9	0.1289	0.1289	0.1289	0.1289	0.1289
RUN_d 6.4	10	0.1414	0.1414	0.1414	0.1414	0.1414
RUN_d 6.5	11	0.2168	0.2168	0.2168	0.2168	0.2168
		1	2	3	4	5

RUN_d 6.0	6	*				
RUN_d 6.1	7	0.1288	*			
RUN_d 6.2	8	0.1207	0.1288	*		
RUN_d 6.3	9	0.1289	0.1370	0.1289	*	
RUN_d 6.4	10	0.1414	0.1494	0.1414	0.1469	*
RUN_d 6.5	11	0.2168	0.2252	0.2168	0.2203	0.2262
		6	7	8	9	10

RUN_d 6.5	11	*
		11

Minimum least significant difference	0.1207
Average least significant difference	0.1445
Maximum least significant difference	0.2262

Graphic iteration of data

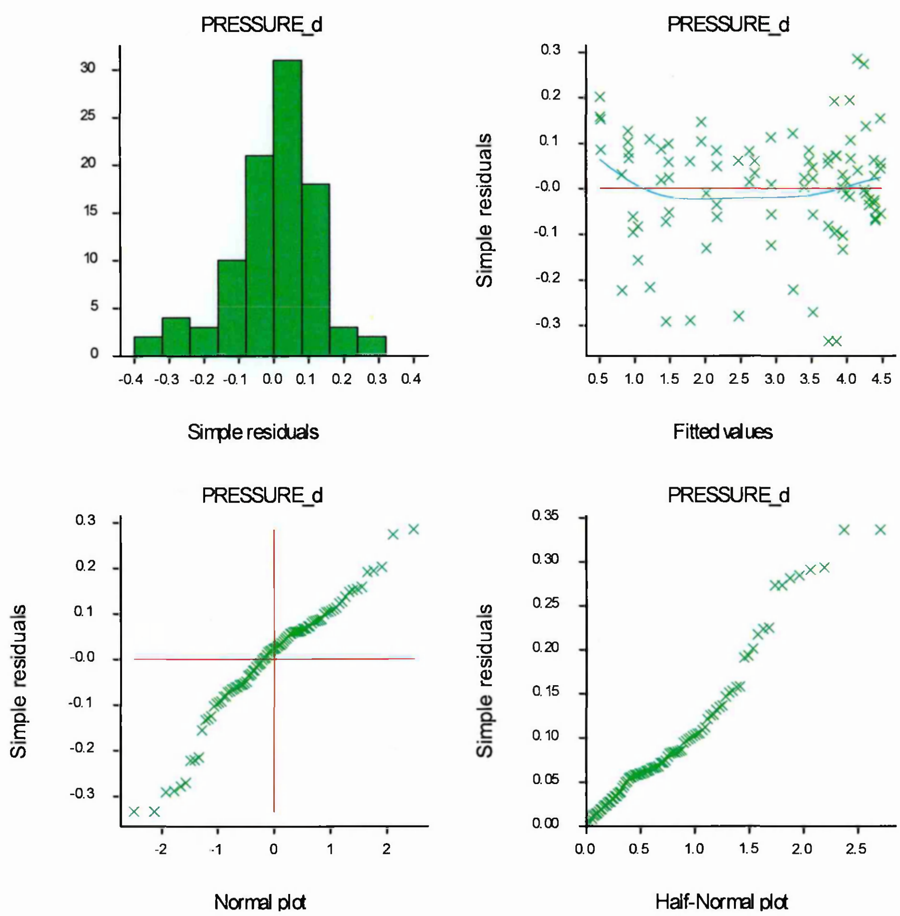


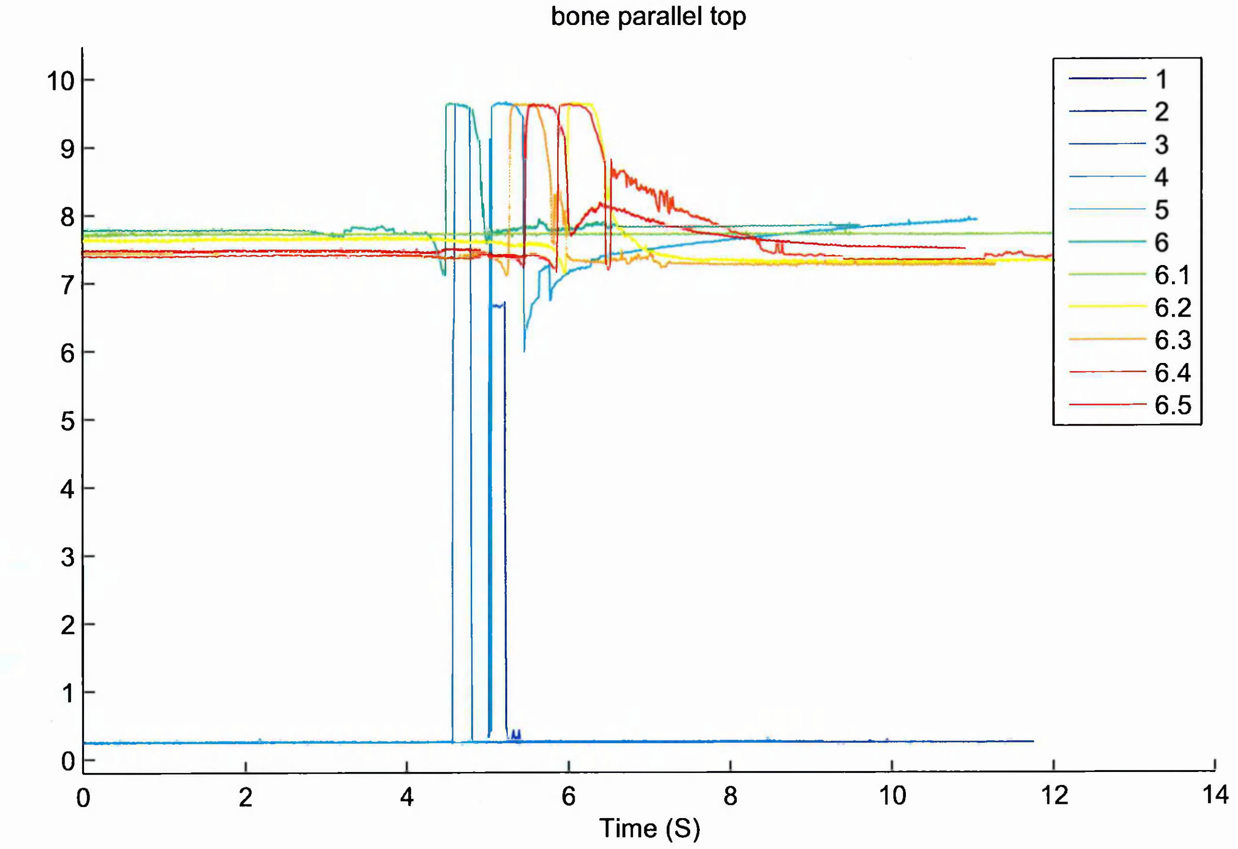
Figure I.4: Residual histogram and scatterplots for analysis of variance of peak pressure data from all load-inflation cases (runs) within the five breakage trials

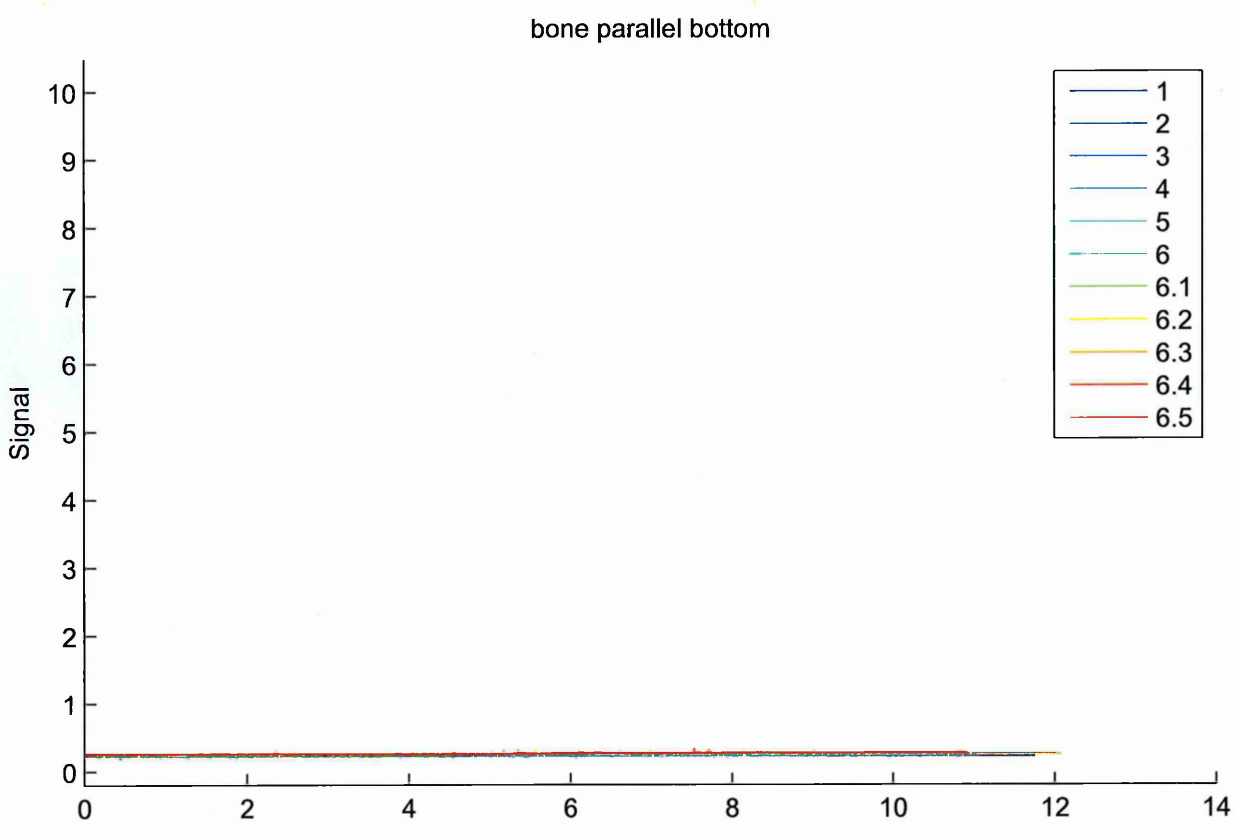
Appendix J: Visual presentation – Lab object breakage indication

The following 28 pages show a visual presentation of the data recorded during the laboratory soil bin breakage trials.

These pages show the electrical signals of the buried objects. Before breakage these signals showed a relative value of the resistance voltage within each circuit. At the moment of object breakage, the resistance within the circuit suddenly increases, and so it is possible to see an indication of this break in a graph of the data. The data was analyzed numerically, but this visual analysis enabled the author to visually assess the outcome of the experiment and identify breakage as well as any issues with the instrumentation system.

Real1


bone parallel top
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
Time (S)
1
2
3
4
5
6
6.1
6.2
6.3
6.4
6.5


bone parallel bottom
Signal
10
9
8
7
6
5
4
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2
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0
0
2
4
6
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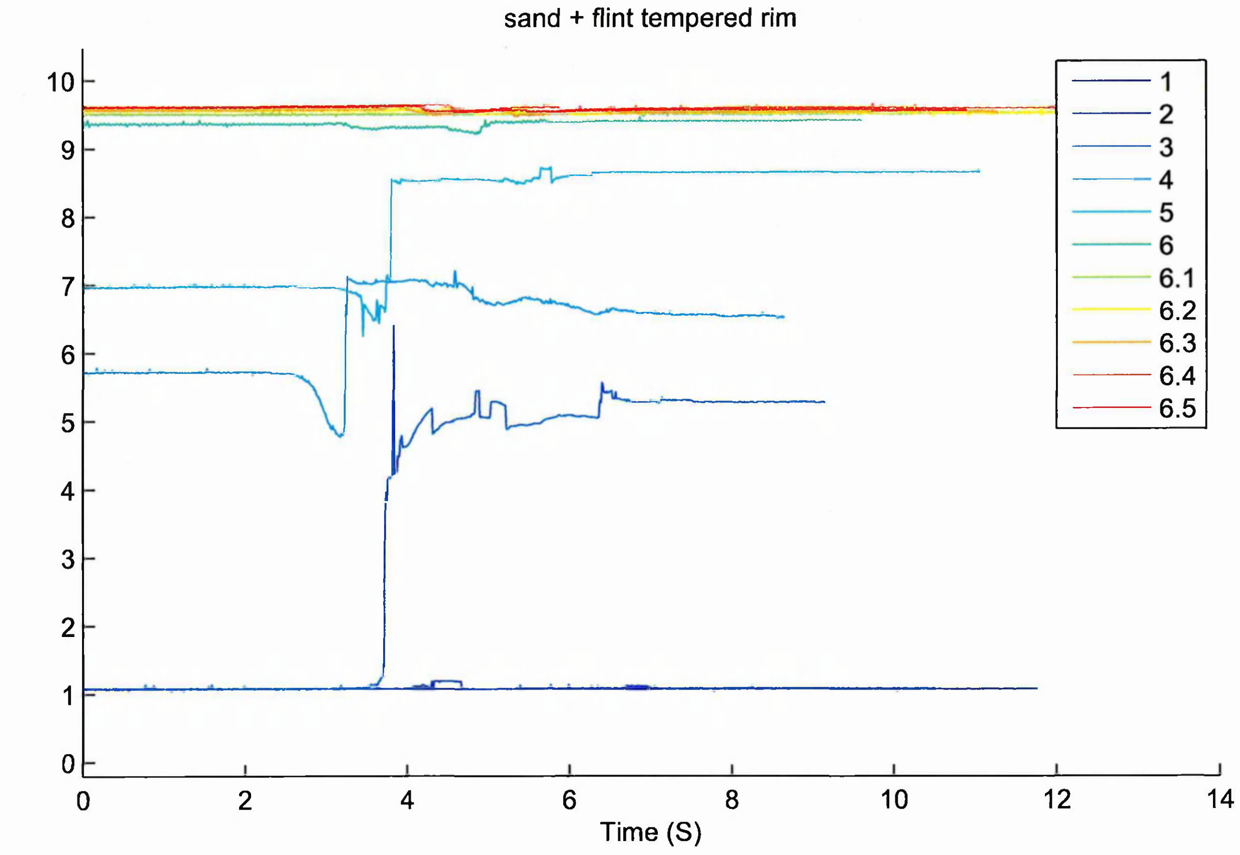
10
12
14
1
2
3
4
5
6
6.1
6.2
6.3
6.4
6.5

Real1


sand + flint tempered rim
10
9
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14
Time (S)
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6.1
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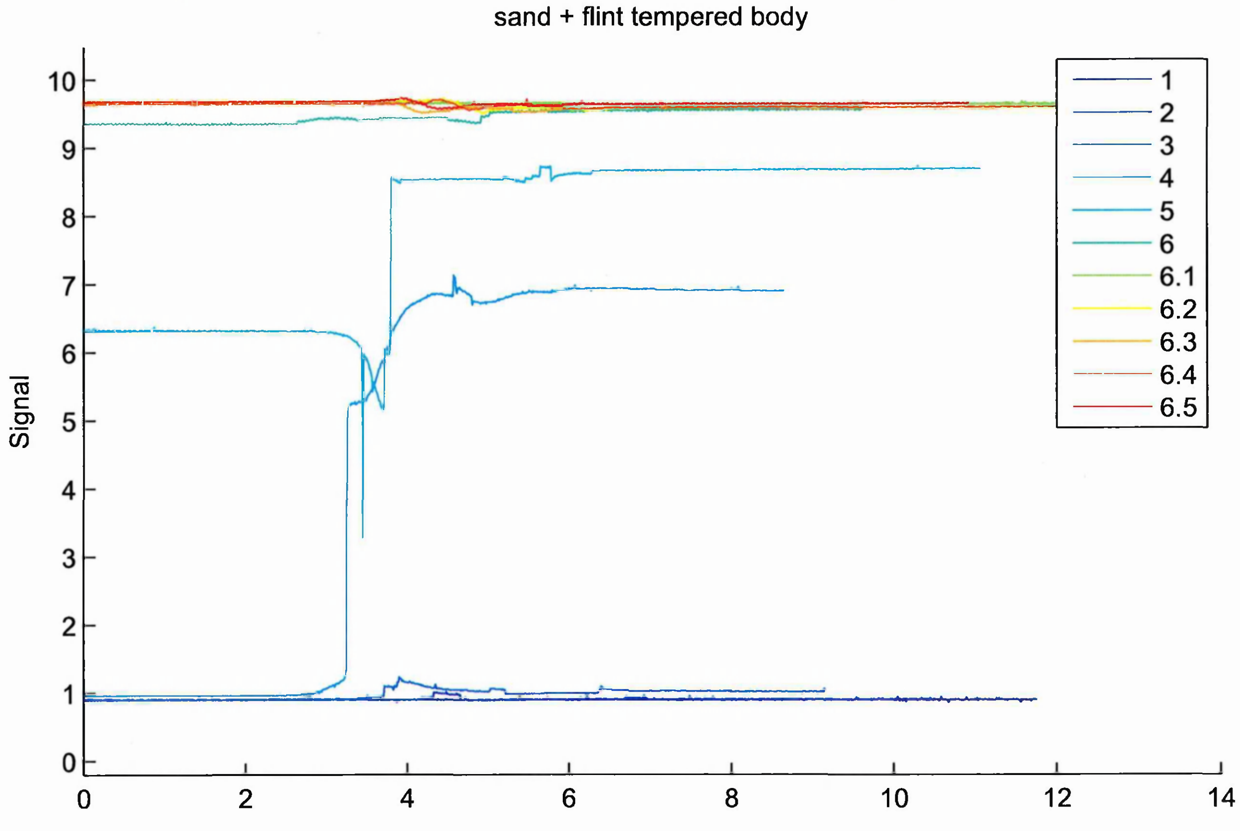
6.3
6.4
6.5


sand + flint tempered body
Signal
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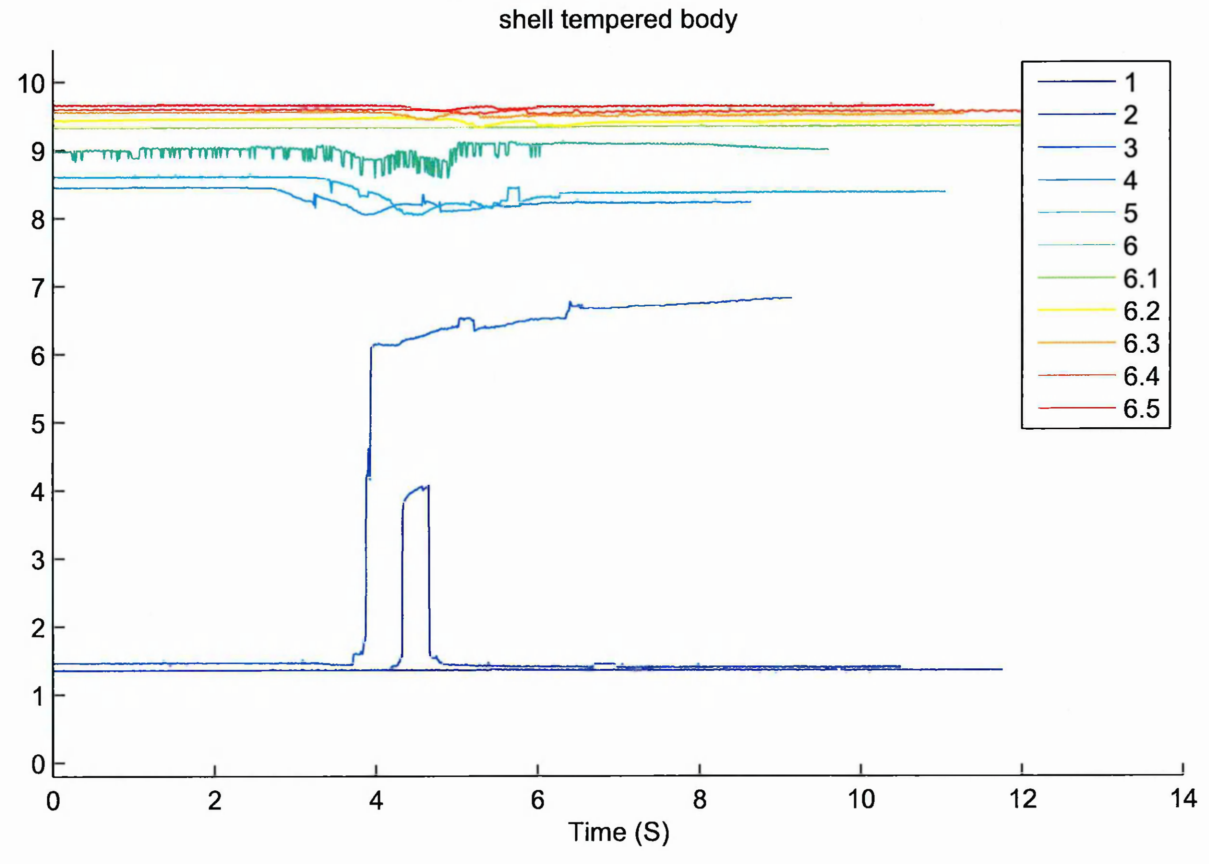
8
10
12
14
1
2
3
4
5
6
6.1
6.2
6.3
6.4
6.5

Real1


shell tempered body
Time (S)
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4
5
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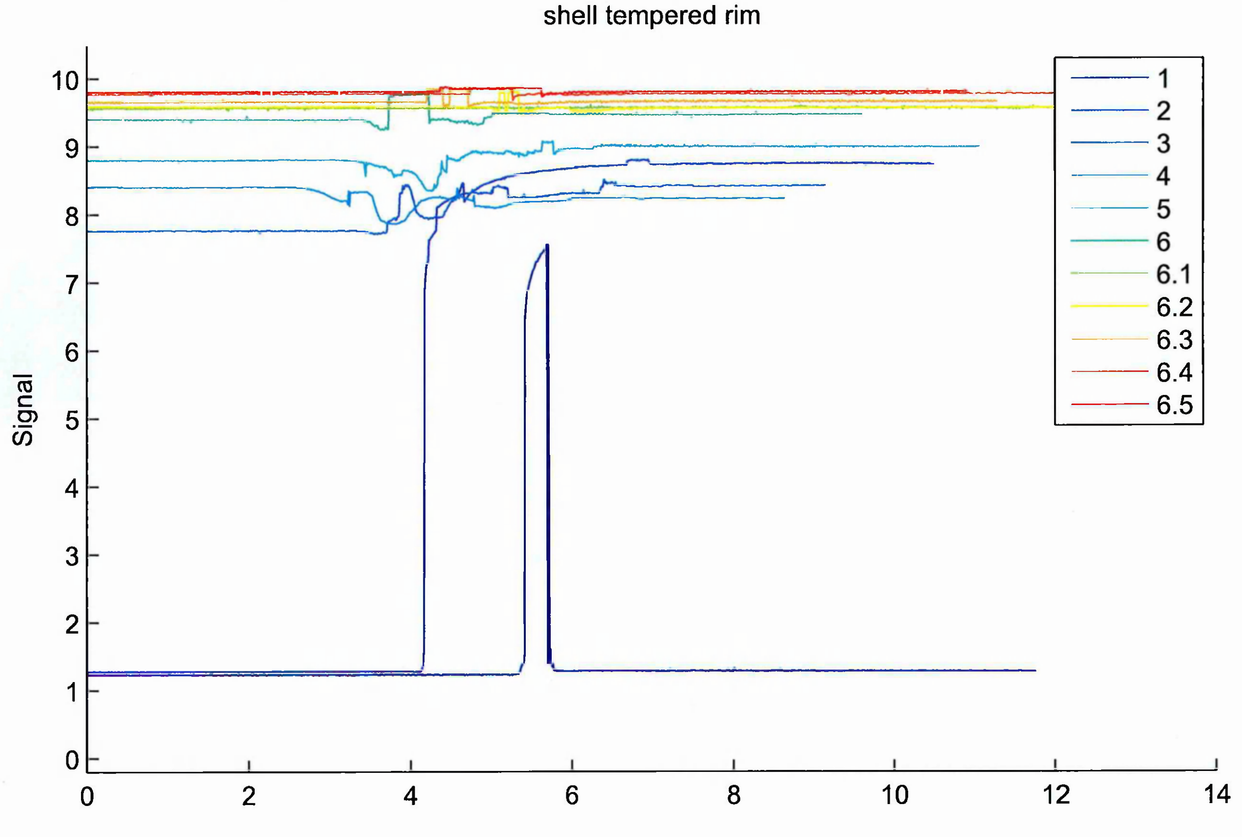
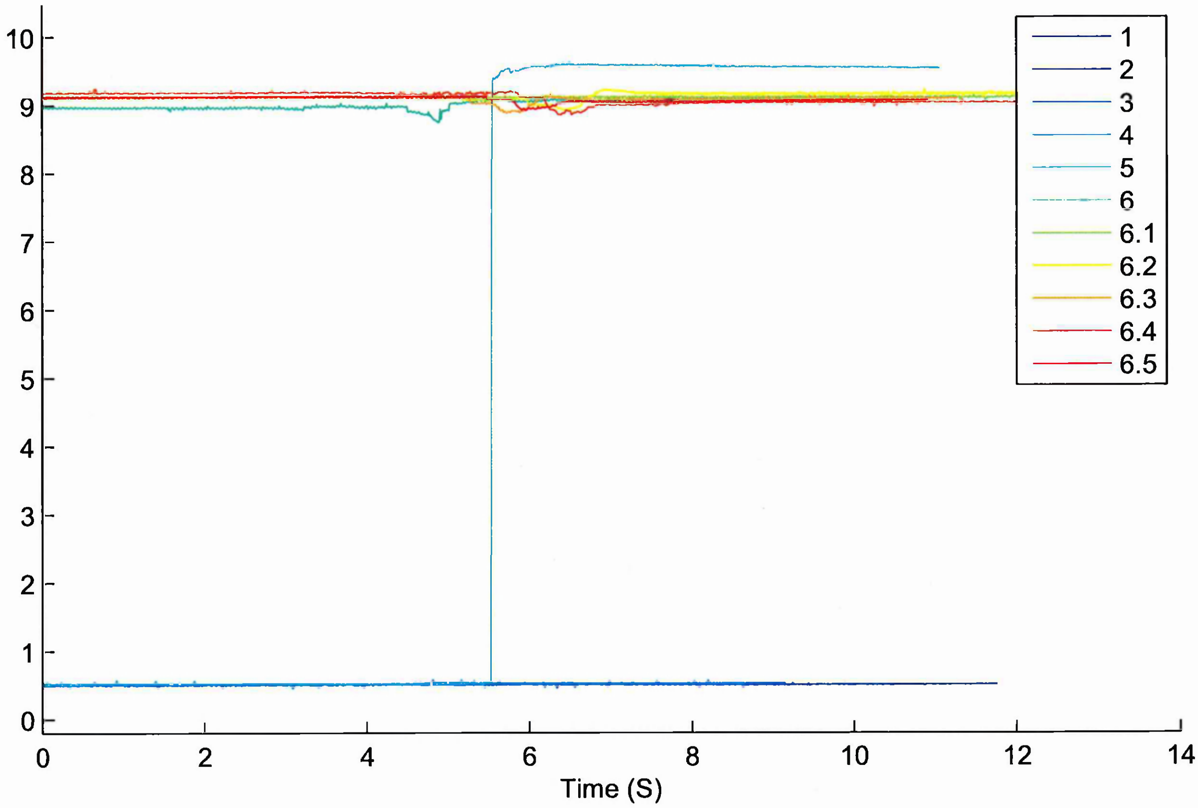
6.1
6.2
6.3
6.4
6.5

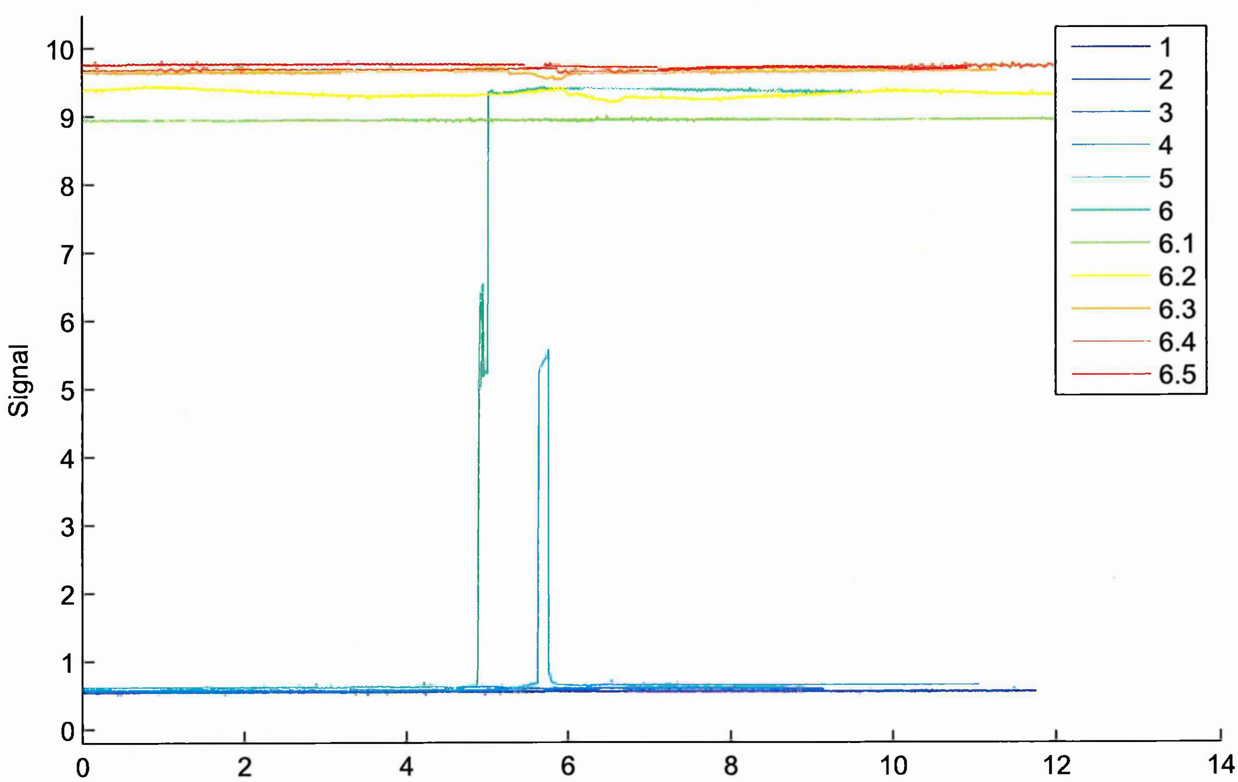

shell tempered rim
Signal
1
2
3
4
5
6
6.1
6.2
6.3
6.4
6.5

Real1

roman thrown rim

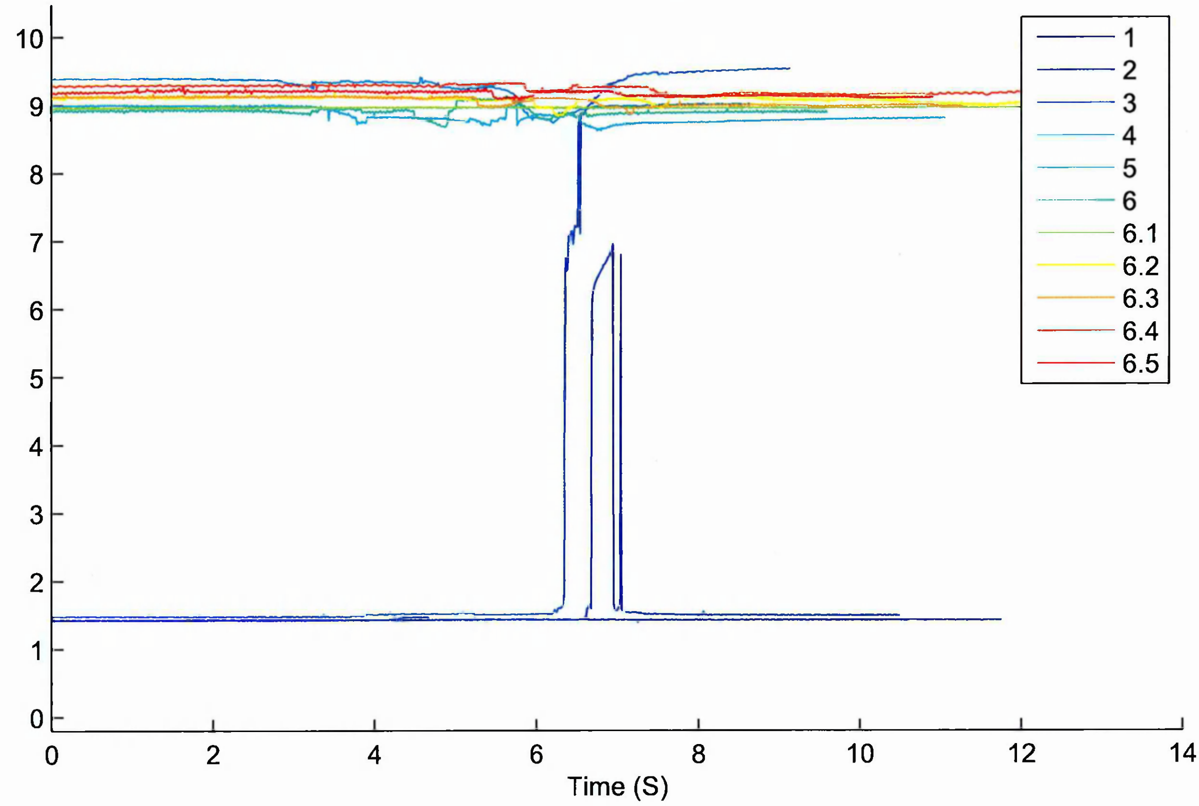


roman thrown body

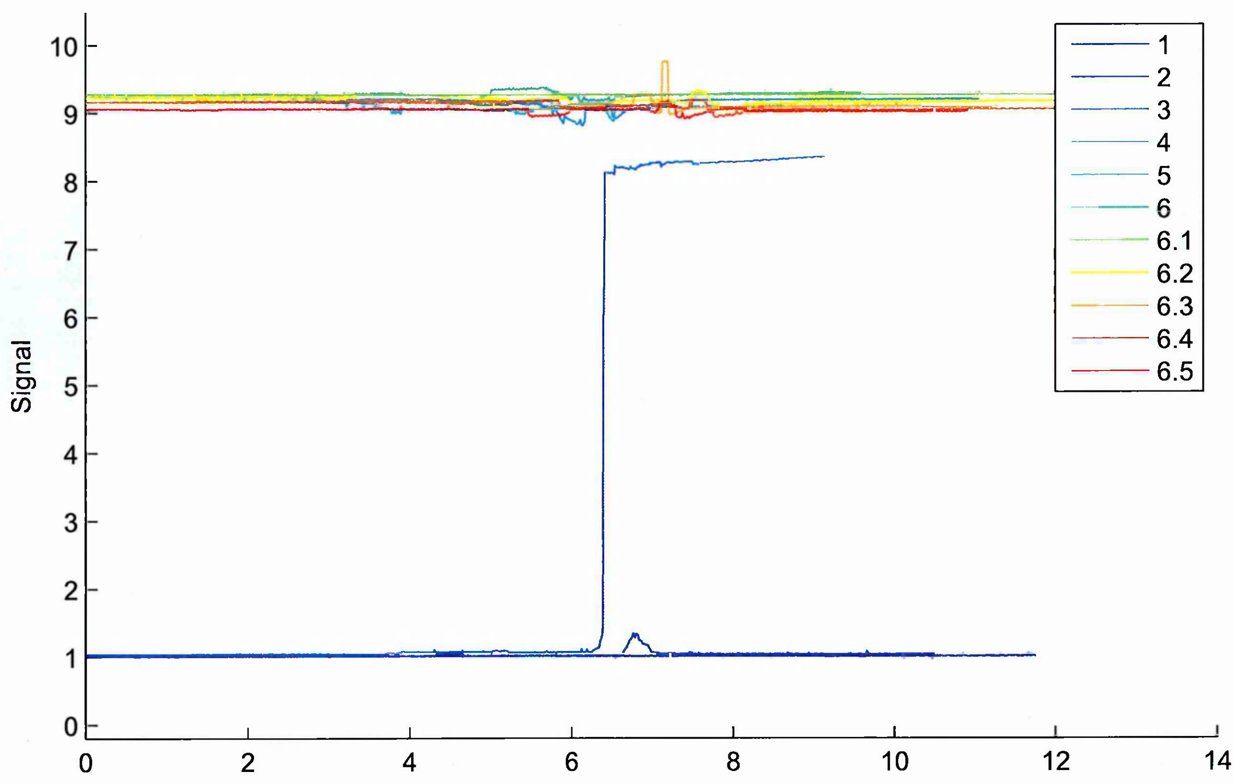


Real1

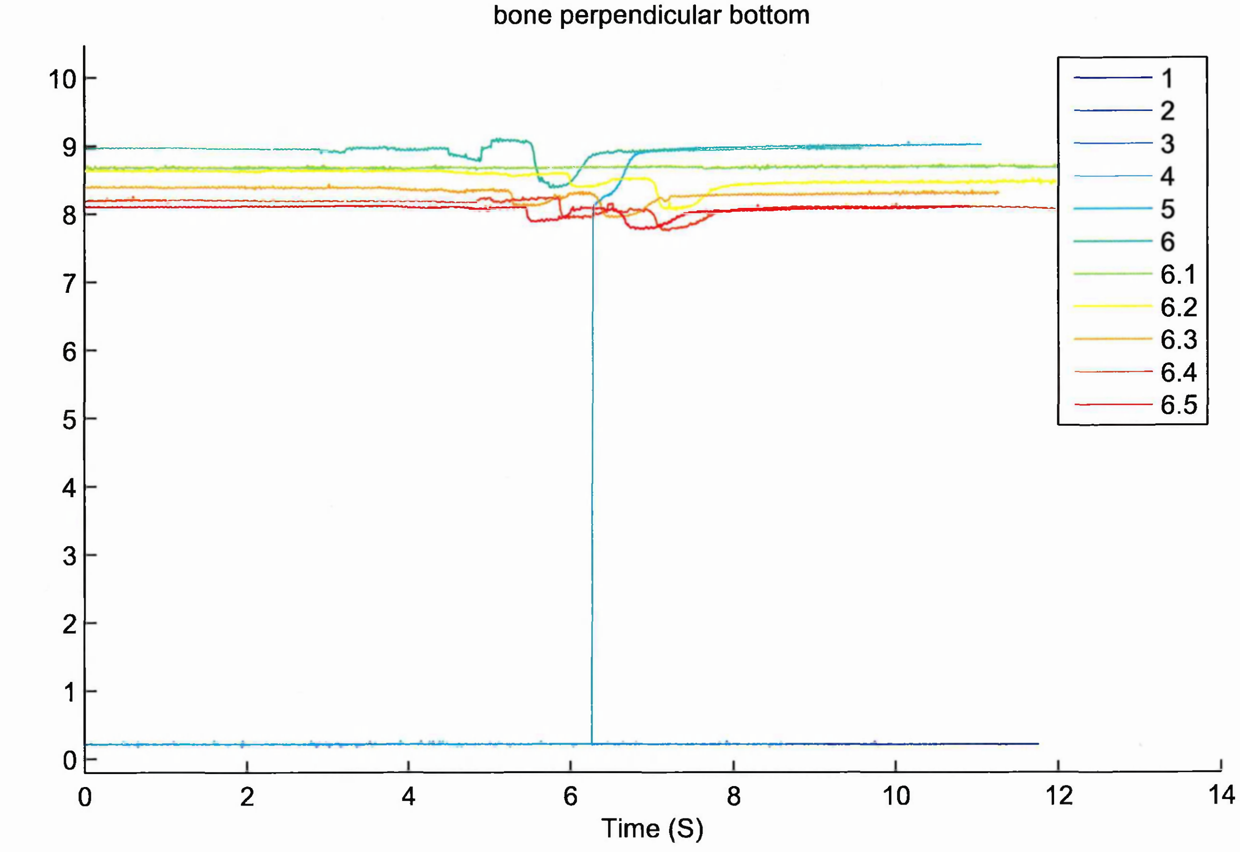
flint beaker rim



flint beaker body



Real1



bone perpendicular bottom
10
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12
14
Time (S)
1
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3
4
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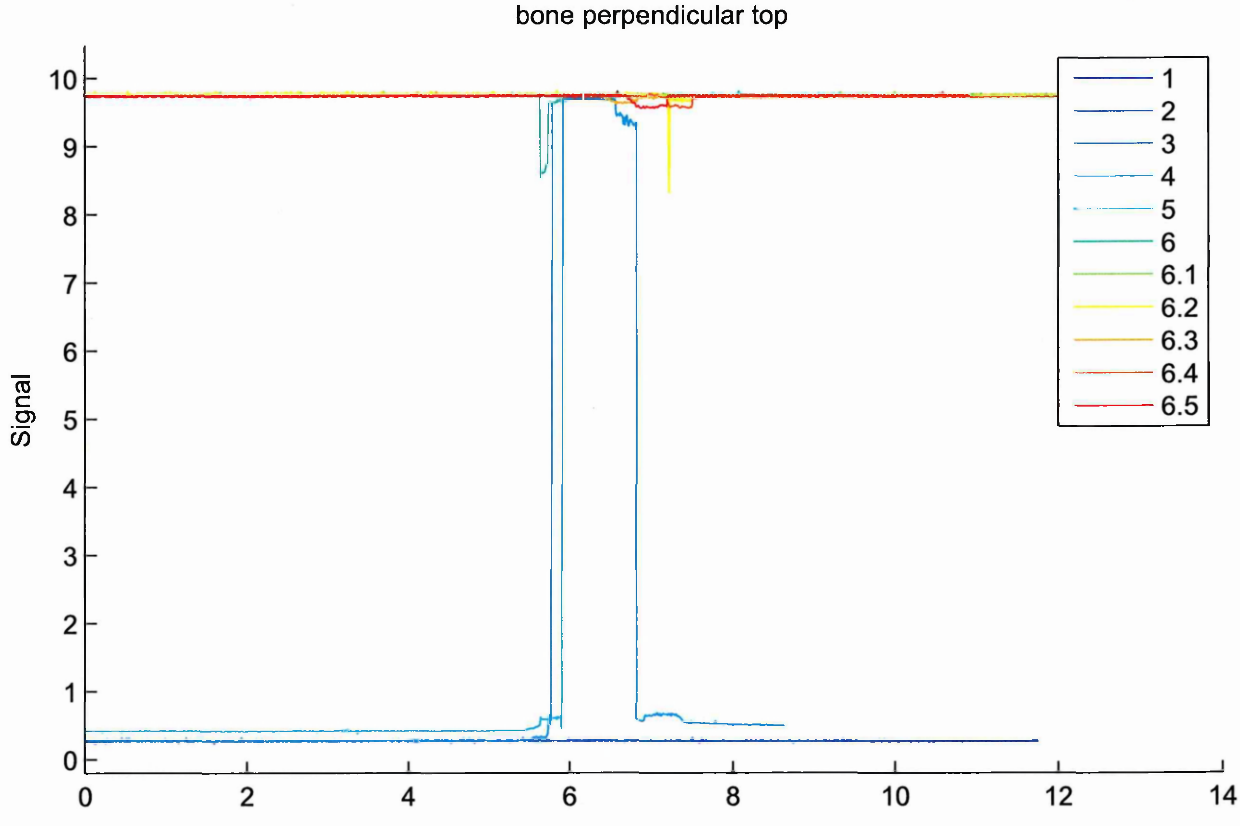
6
6.1
6.2
6.3
6.4
6.5



bone perpendicular top
Signal
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9
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2
4
6
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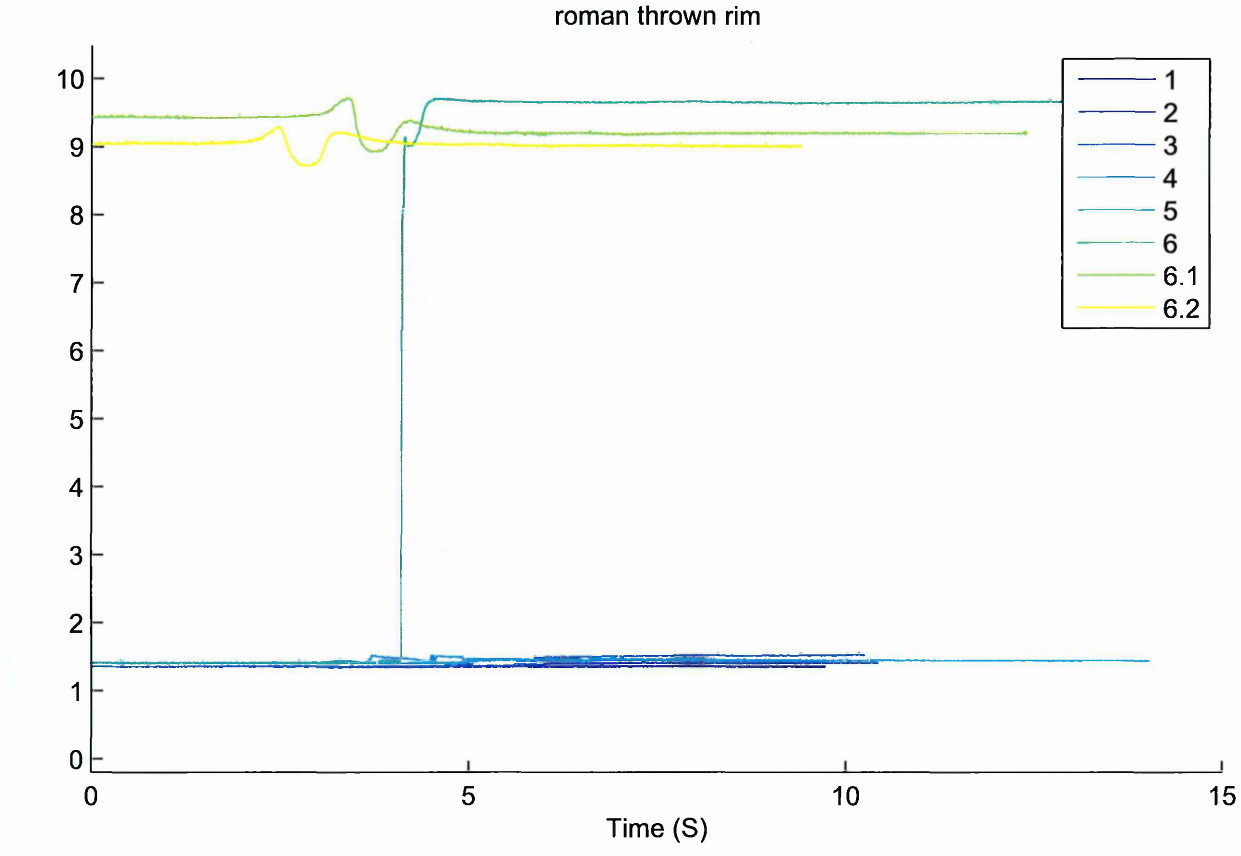
10
12
14
1
2
3
4
5
6
6.1
6.2
6.3
6.4
6.5

Real2



roman thrown rim
10
9
8
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6
5
4
3
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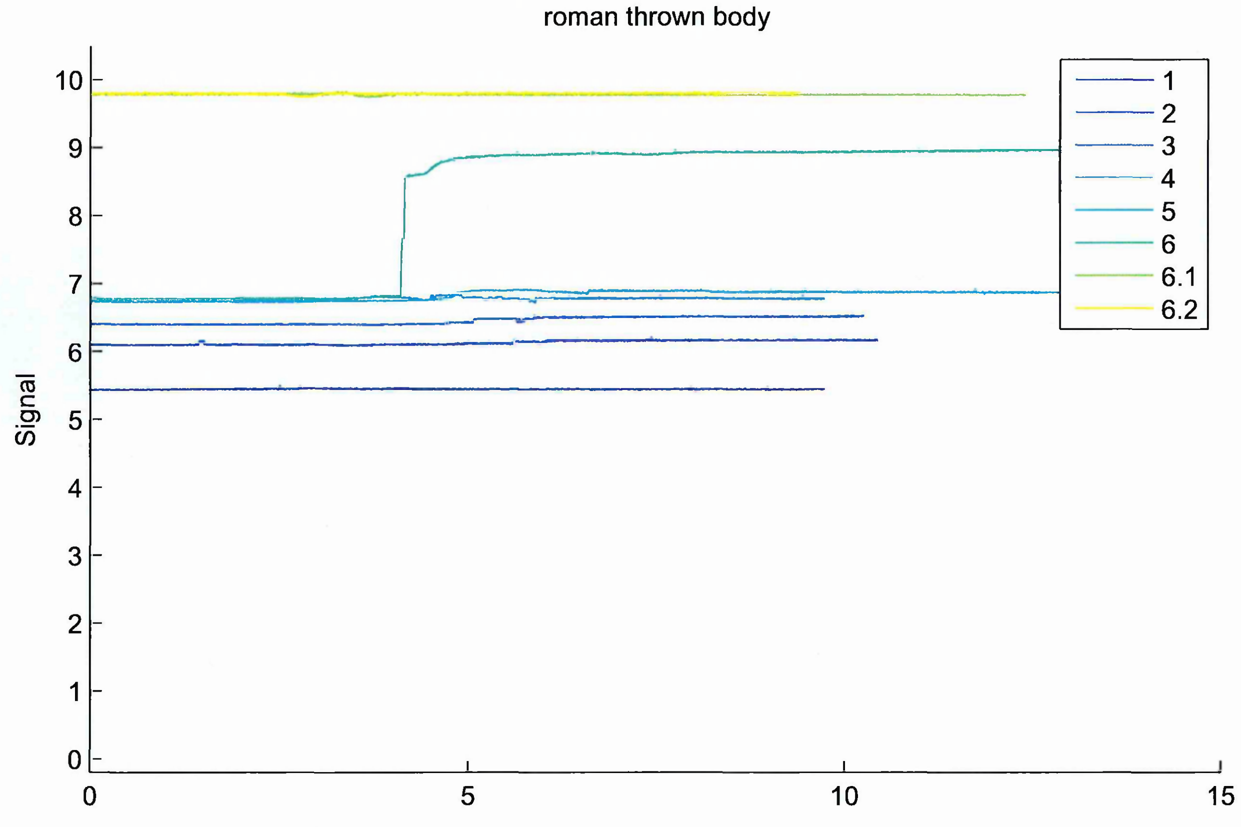
1
0
0
5
10
15
Time (S)
1
2
3
4
5
6
6.1
6.2



roman thrown body
Signal
10
9
8
7
6
5
4
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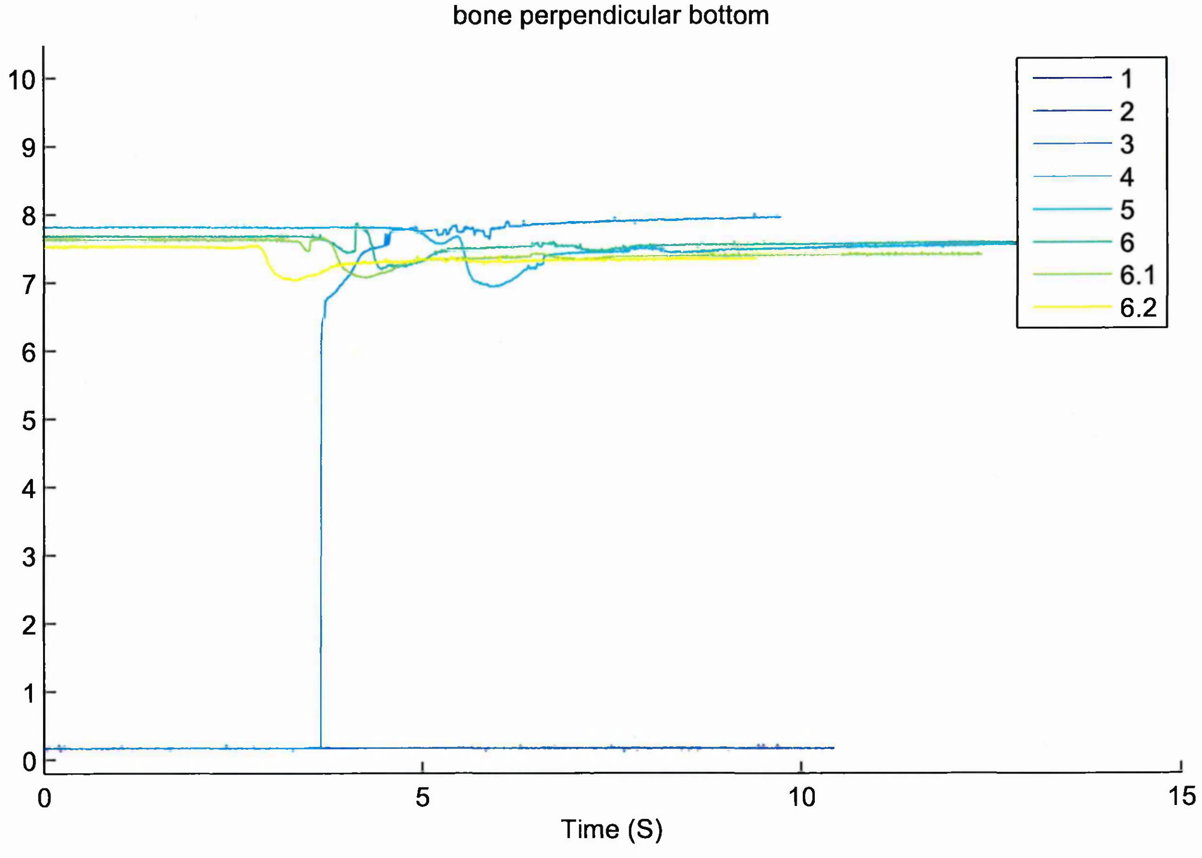
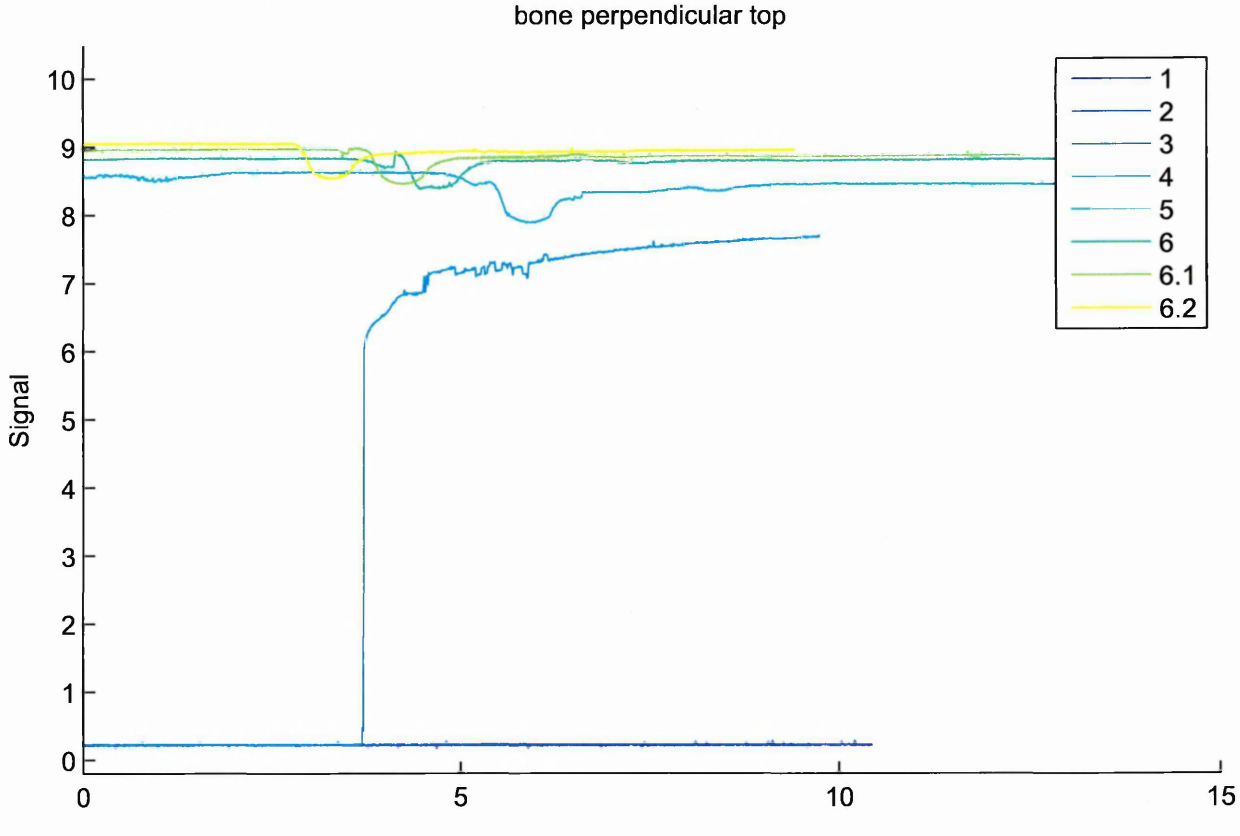
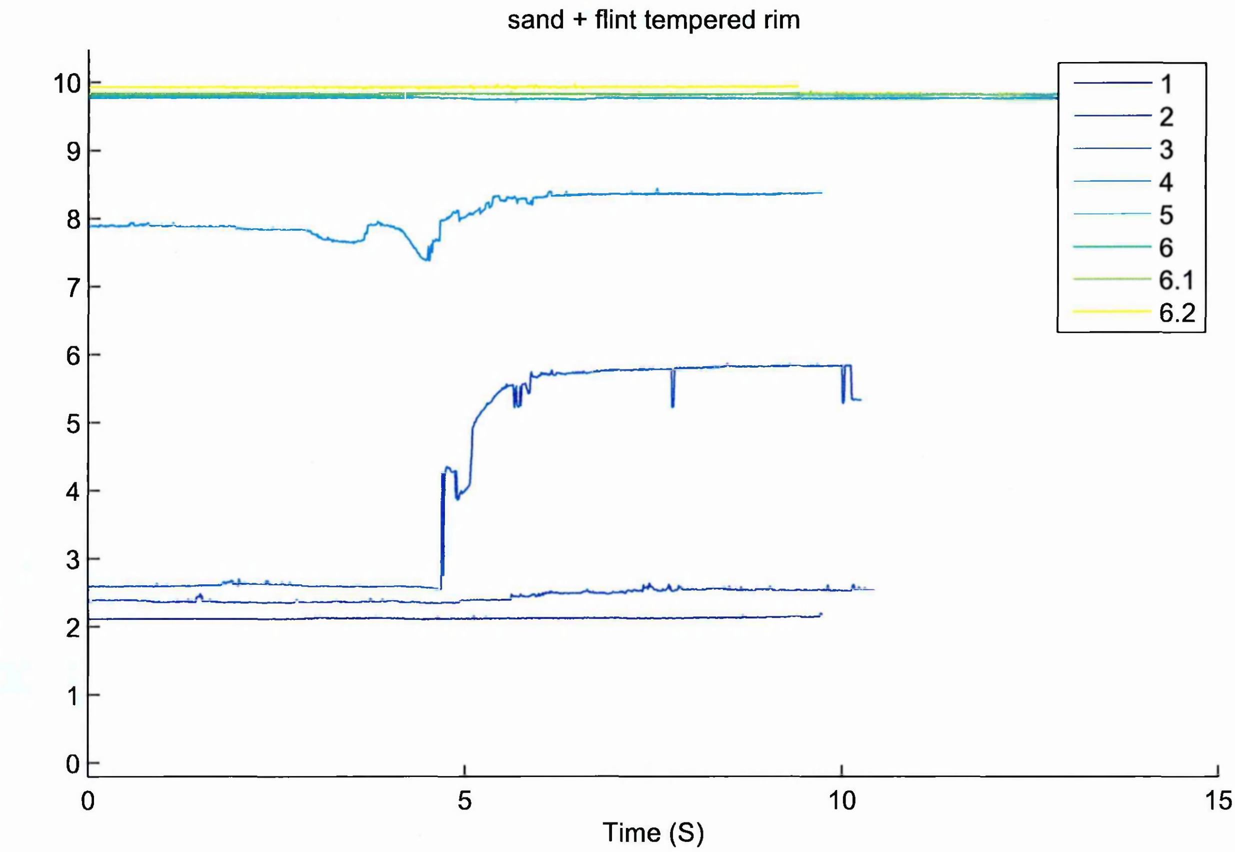
2
1
0
0
5
10
15
1
2
3
4
5
6
6.1
6.2

Real2

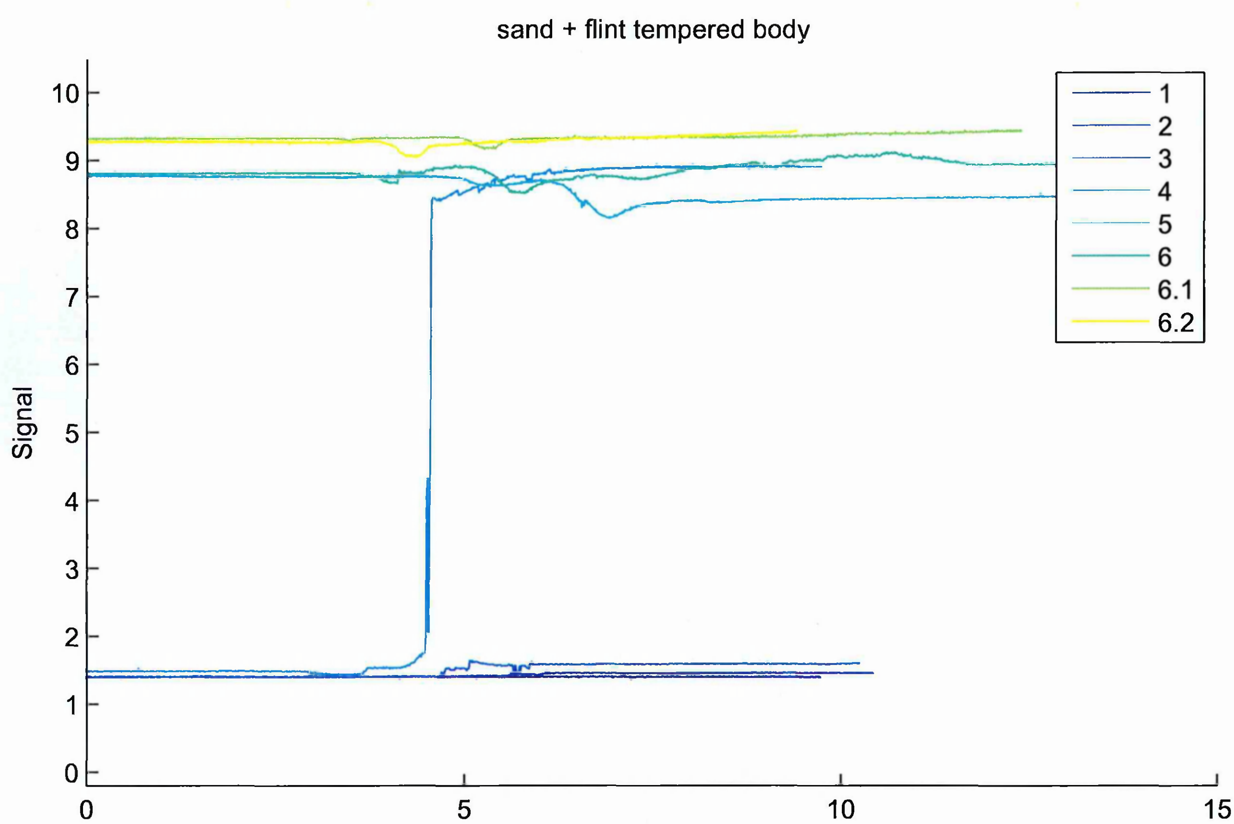

bone perpendicular bottom
10
9
8
7
6
5
4
3
2
1
0
0
5
10
15
Time (S)
1
2
3
4
5
6
6.1
6.2


bone perpendicular top
Signal
10
9
8
7
6
5
4
3
2
1
0
0
5
10
15
1
2
3
4
5
6
6.1
6.2

Real2

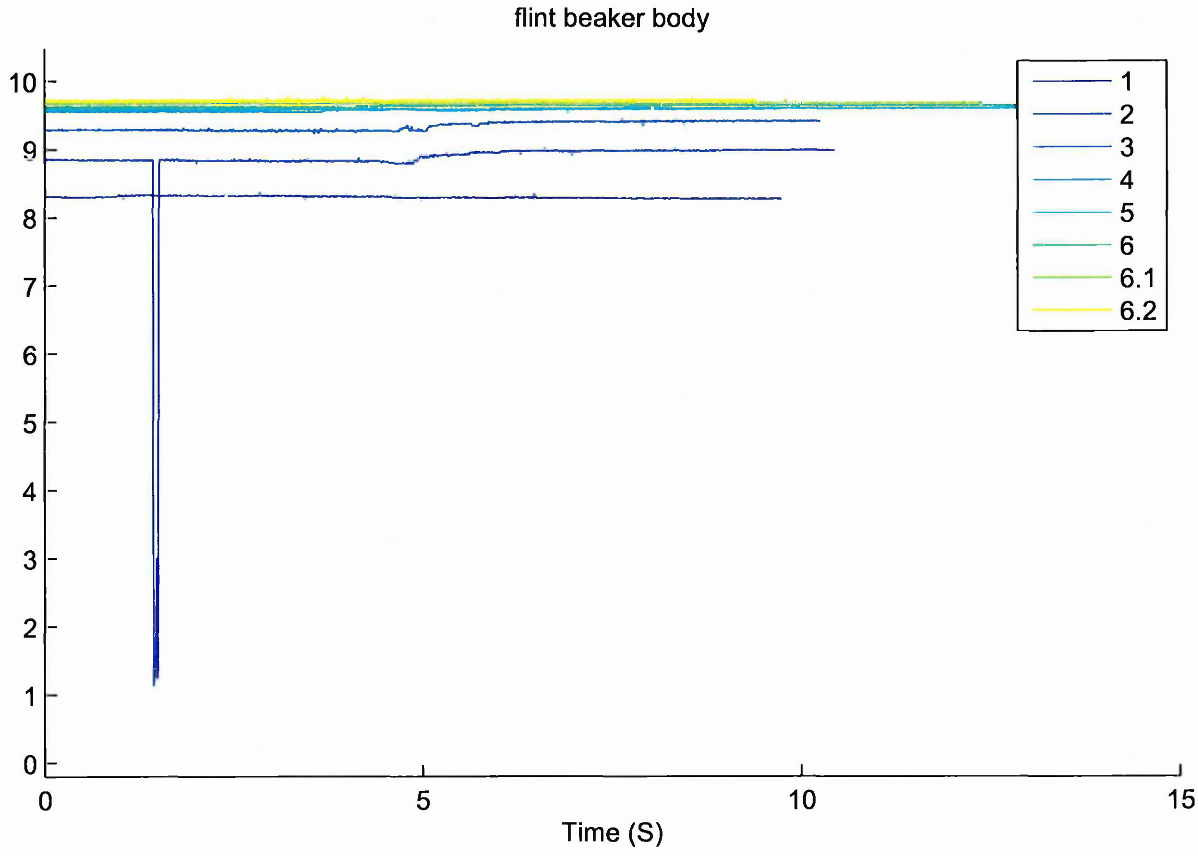


sand + flint tempered rim
0
1
2
3
4
5
6
7
8
9
10
0
5
10
15
Time (S)
1
2
3
4
5
6
6.1
6.2

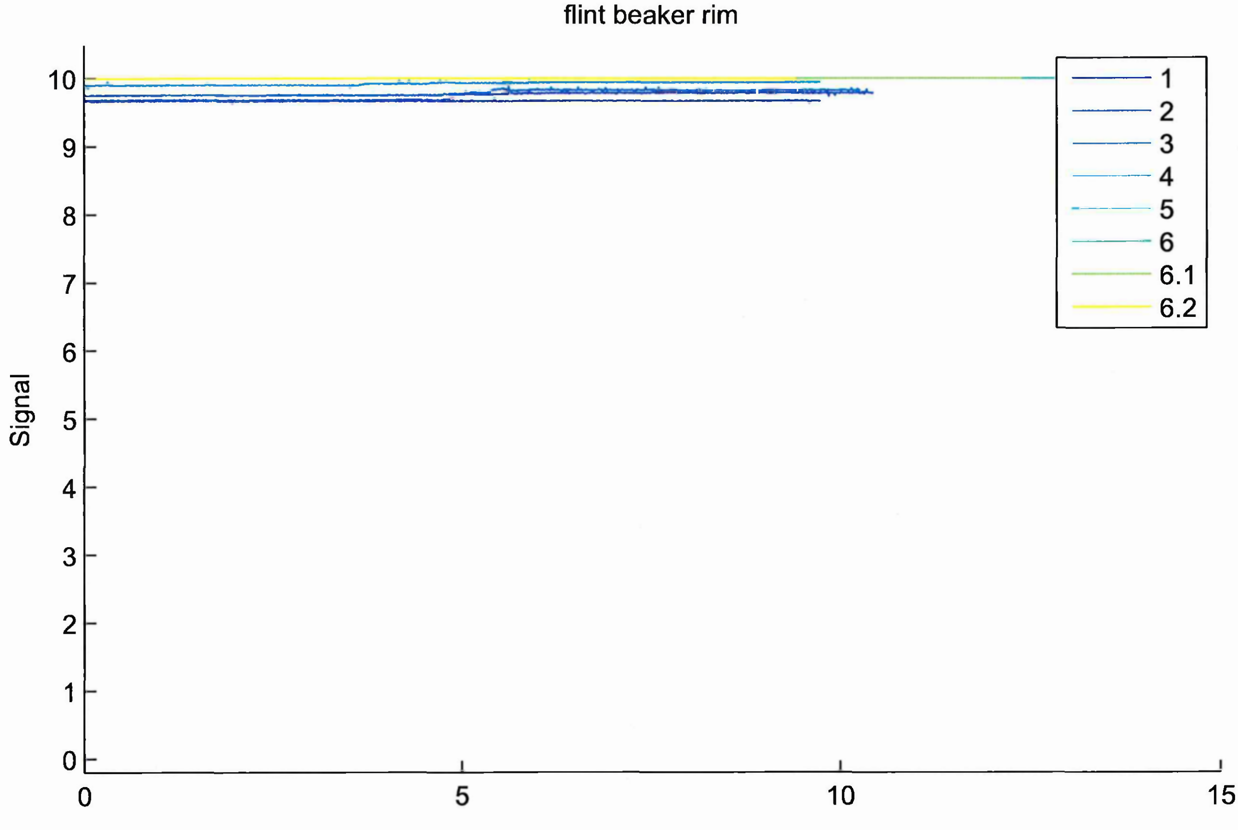


sand + flint tempered body
Signal
0
1
2
3
4
5
6
7
8
9
10
0
5
10
15
1
2
3
4
5
6
6.1
6.2

Real2

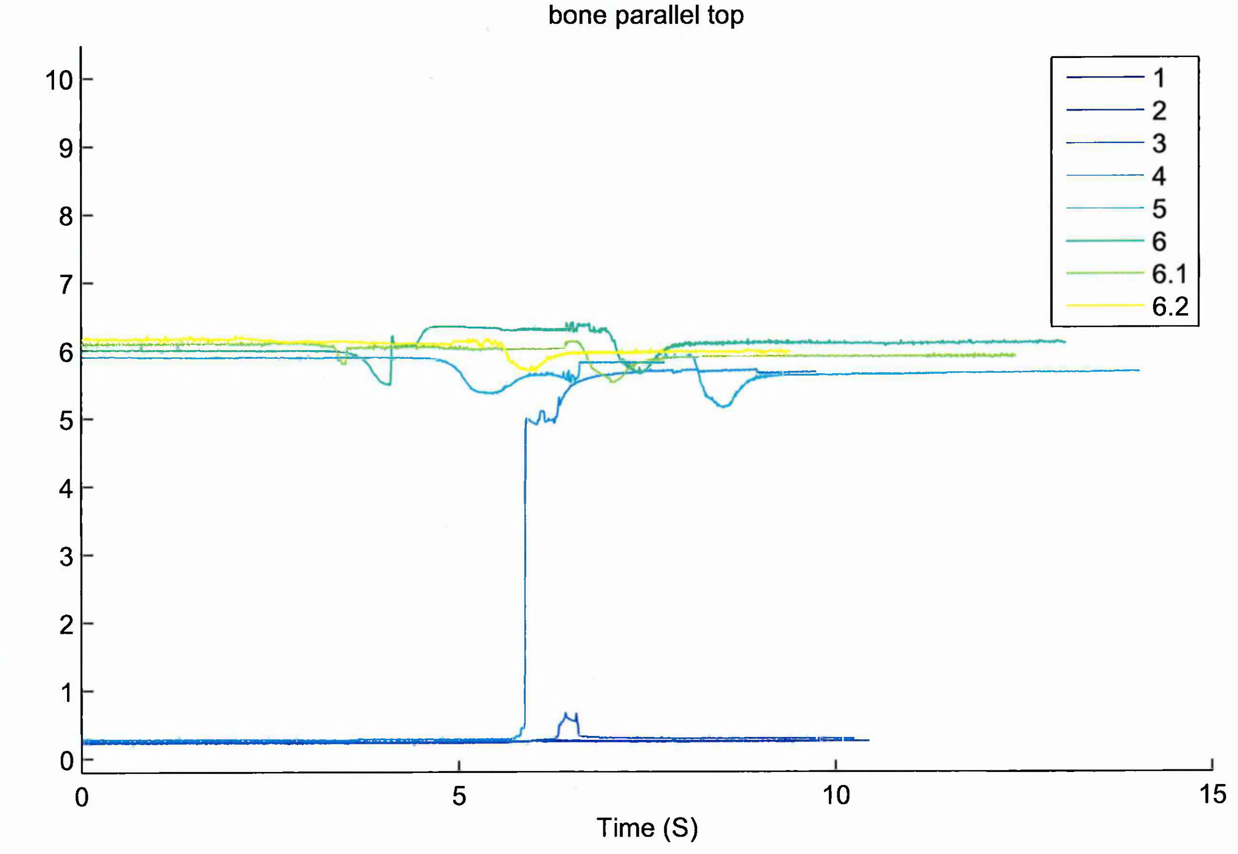


flint beaker body
10
9
8
7
6
5
4
3
2
1
0
0
5
10
15
Time (S)
1
2
3
4
5
6
6.1
6.2

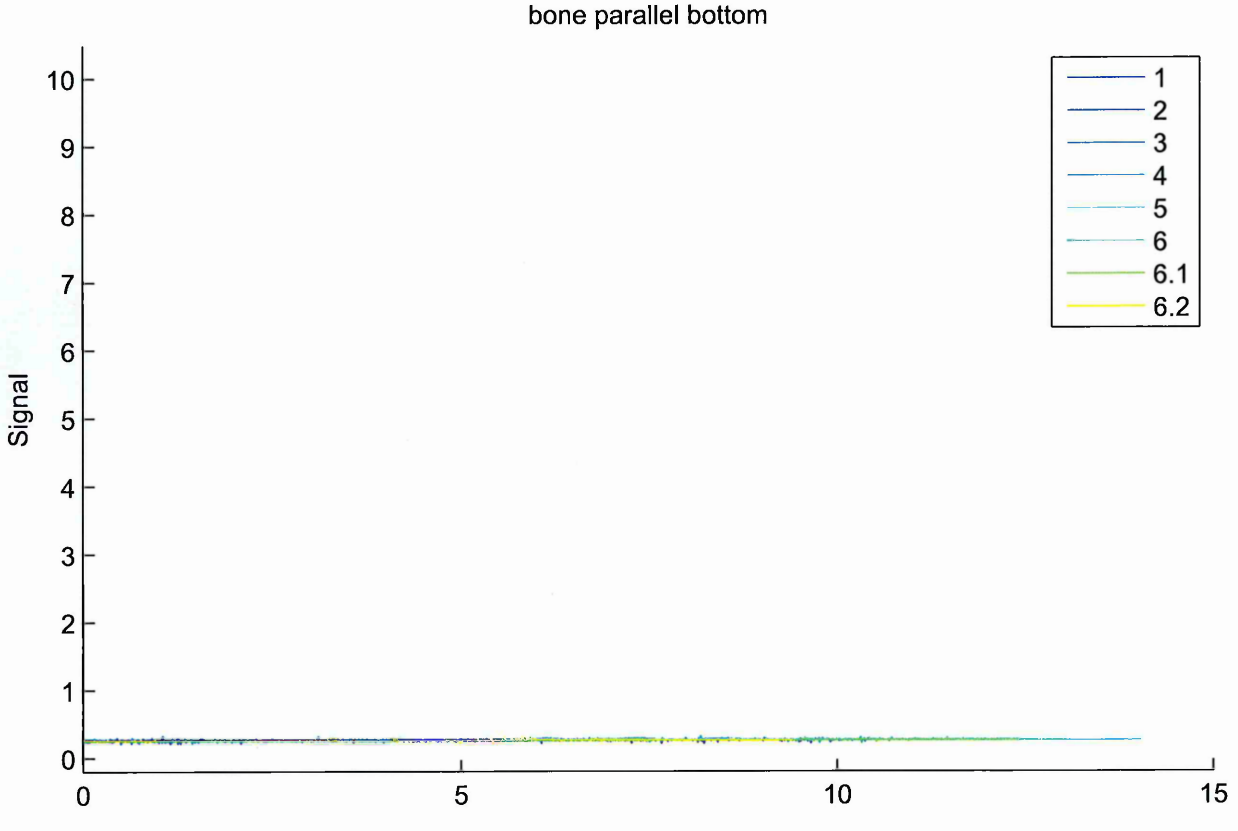


flint beaker rim
Signal
10
9
8
7
6
5
4
3
2
1
0
0
5
10
15
1
2
3
4
5
6
6.1
6.2

Real2

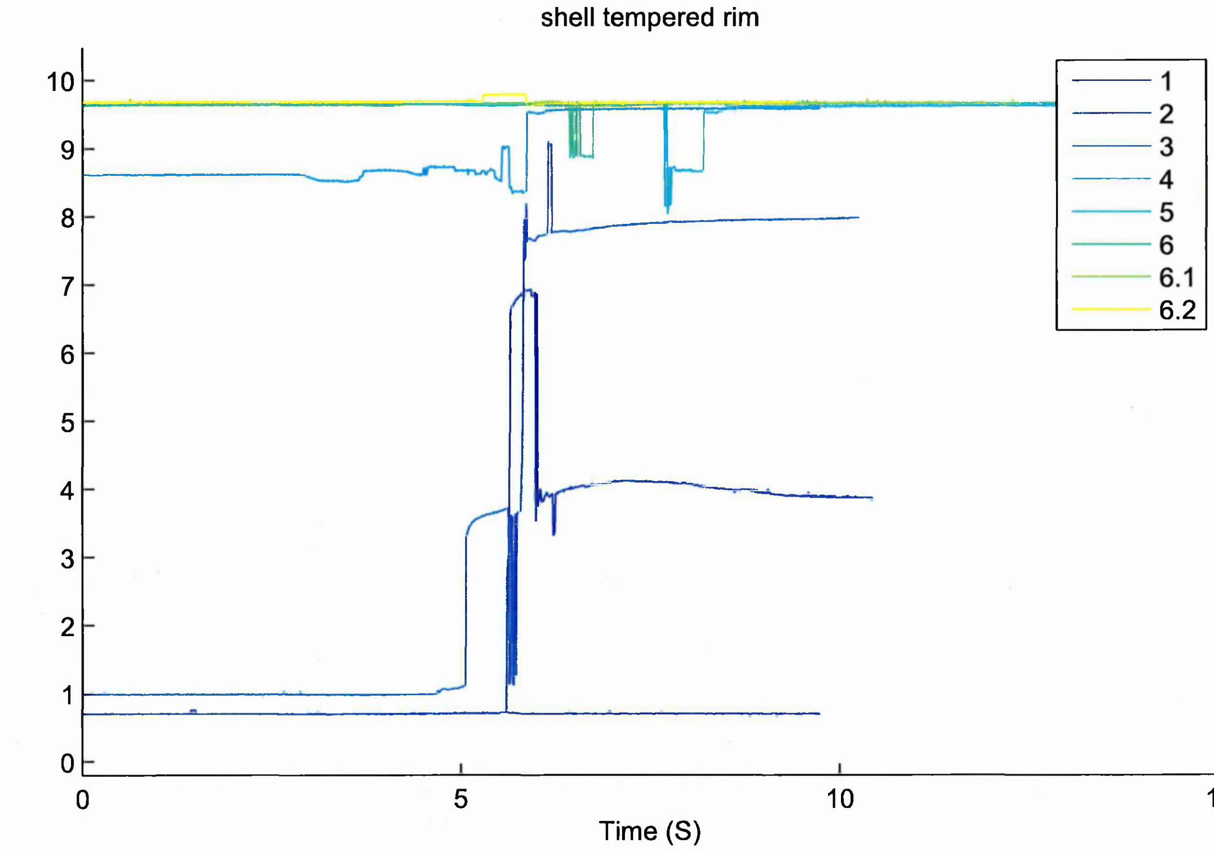


bone parallel top
10
9
8
7
6
5
4
3
2
1
0
0
5
10
15
Time (S)
1
2
3
4
5
6
6.1
6.2

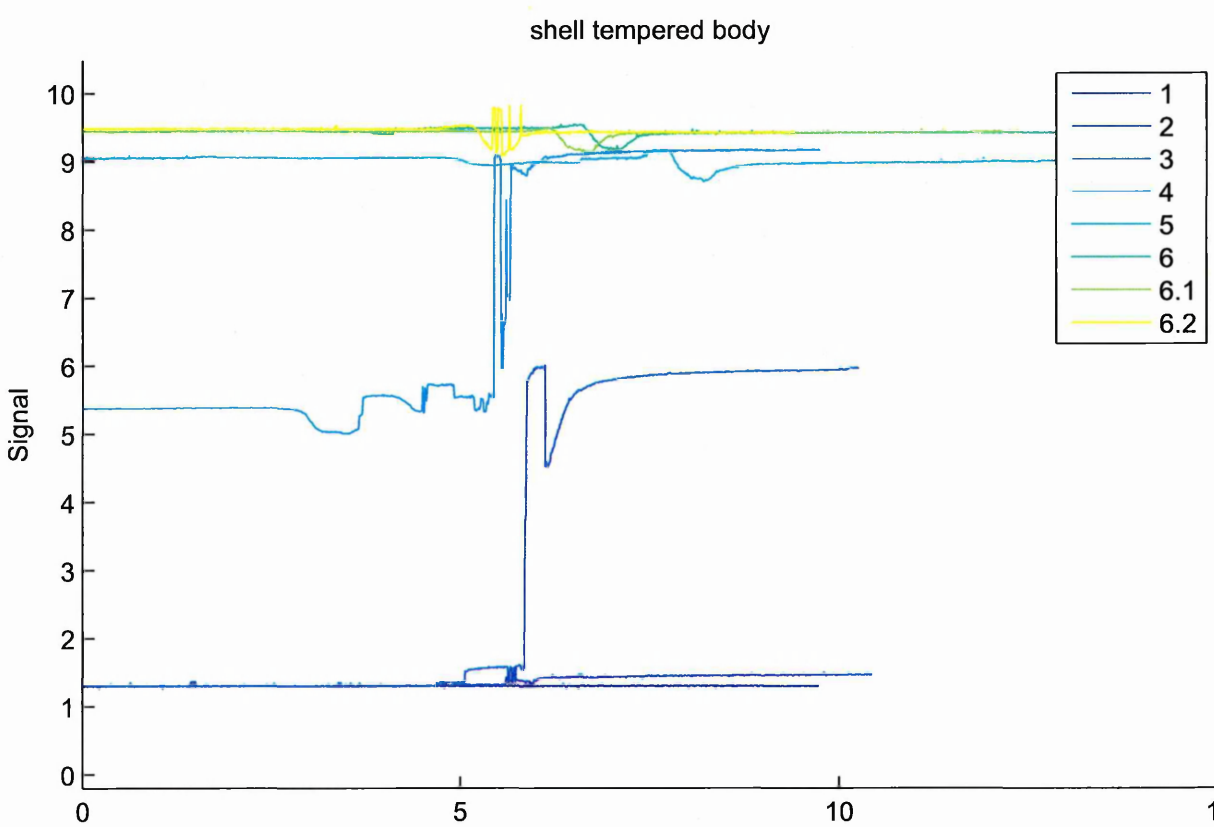


bone parallel bottom
Signal
10
9
8
7
6
5
4
3
2
1
0
0
5
10
15
1
2
3
4
5
6
6.1
6.2

Real2

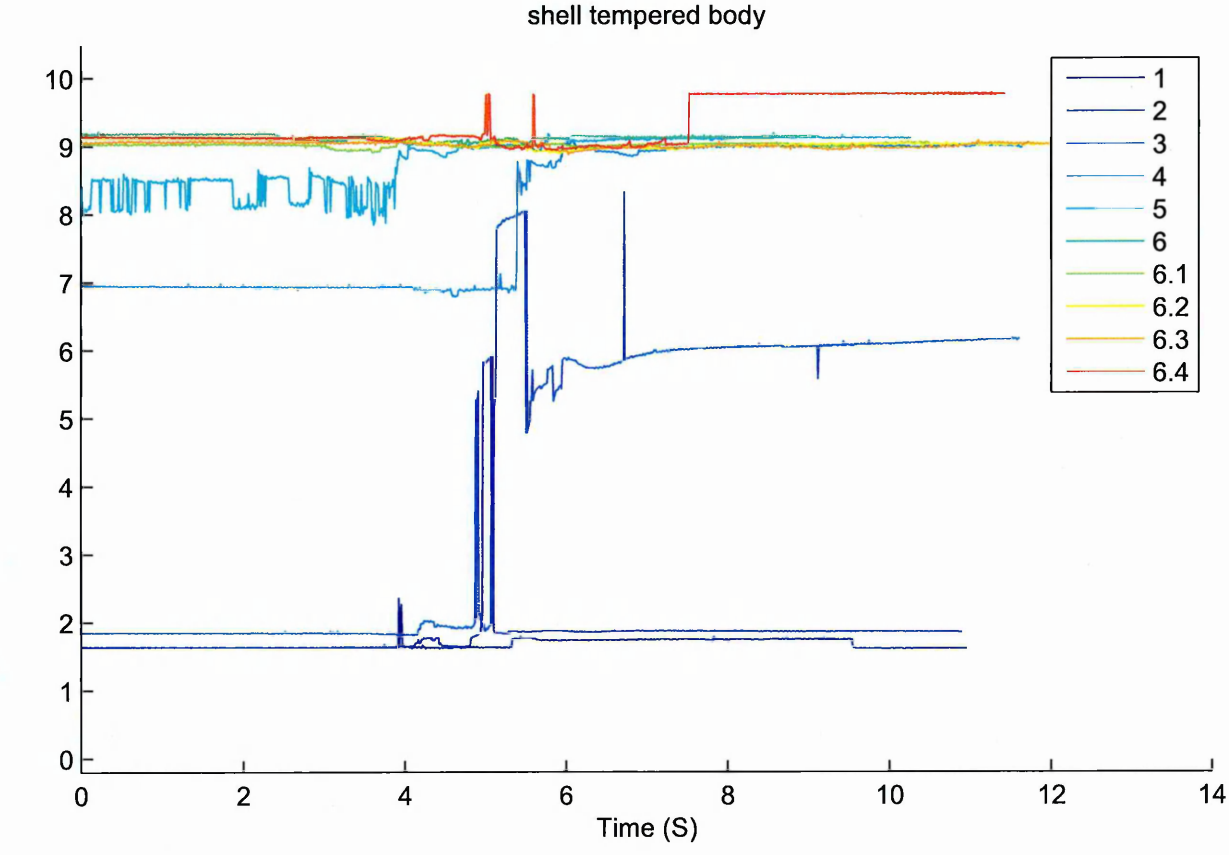


shell tempered rim
10
9
8
7
6
5
4
3
2
1
0
0
5
10
15
Time (S)
1
2
3
4
5
6
6.1
6.2

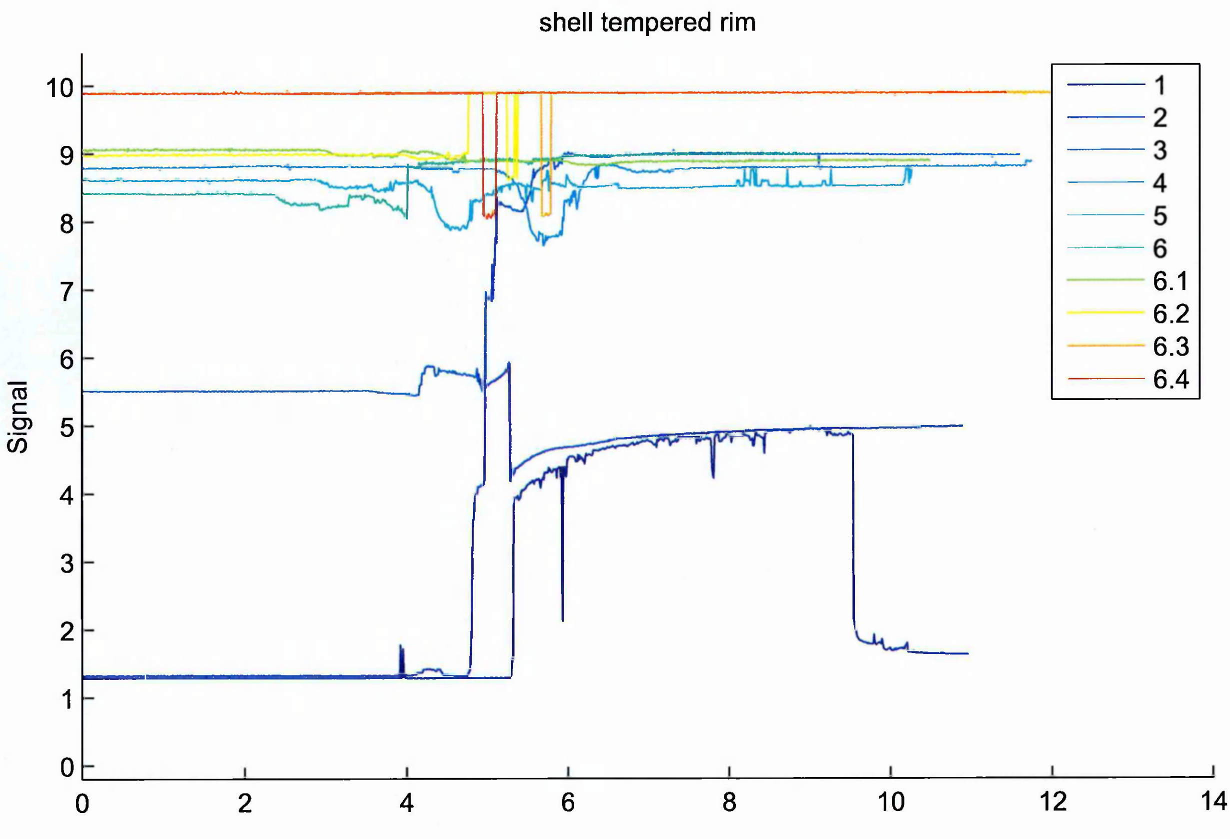


shell tempered body
Signal
10
9
8
7
6
5
4
3
2
1
0
0
5
10
15
1
2
3
4
5
6
6.1
6.2

Real3

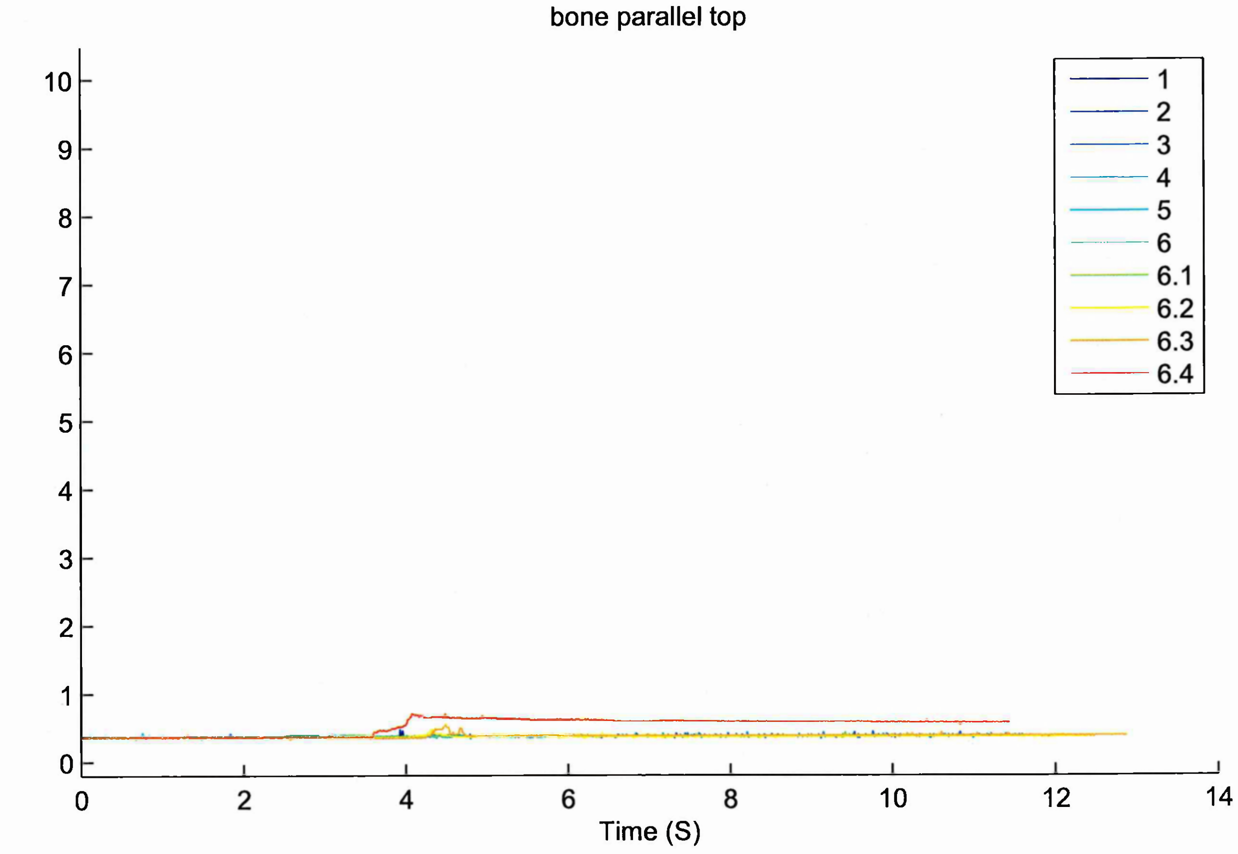


shell tempered body
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
Time (S)
1
2
3
4
5
6
6.1
6.2
6.3
6.4

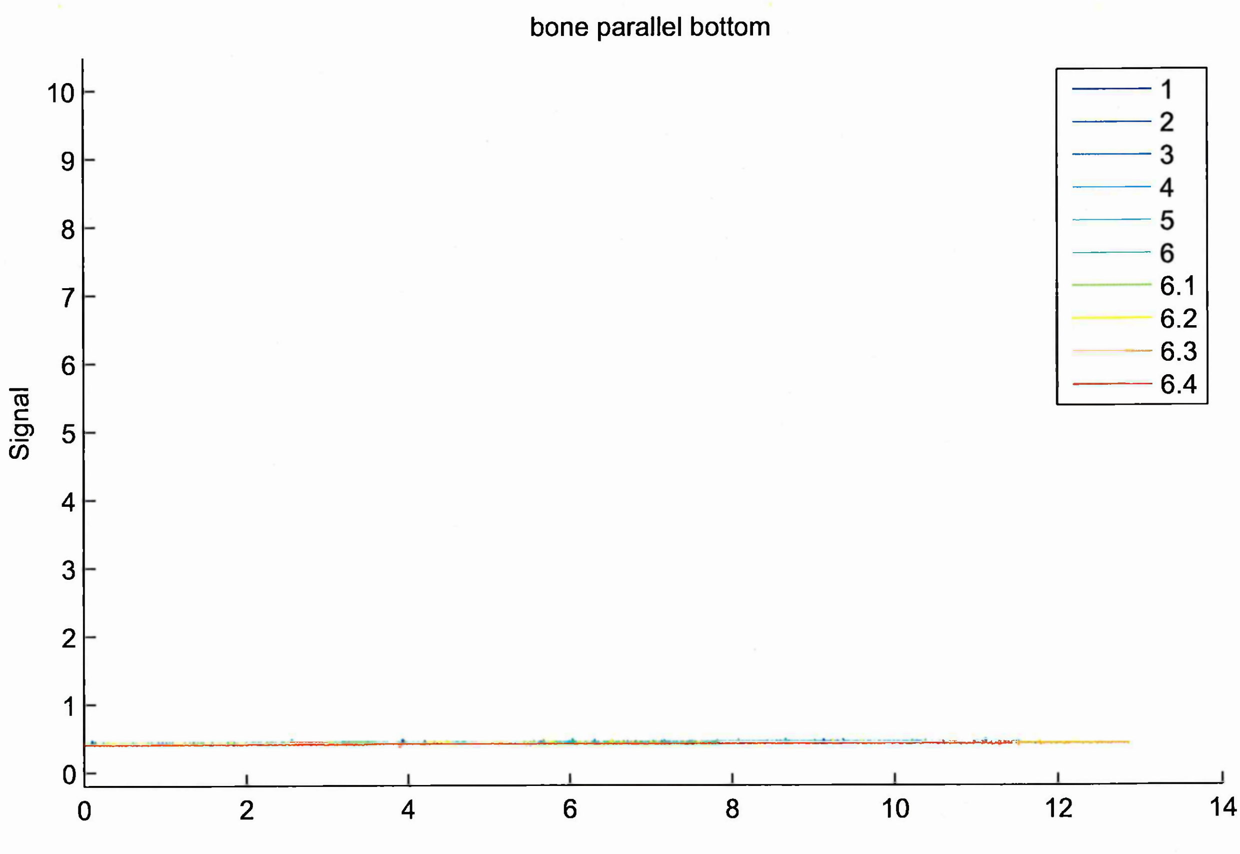


shell tempered rim
Signal
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
1
2
3
4
5
6
6.1
6.2
6.3
6.4

Real3



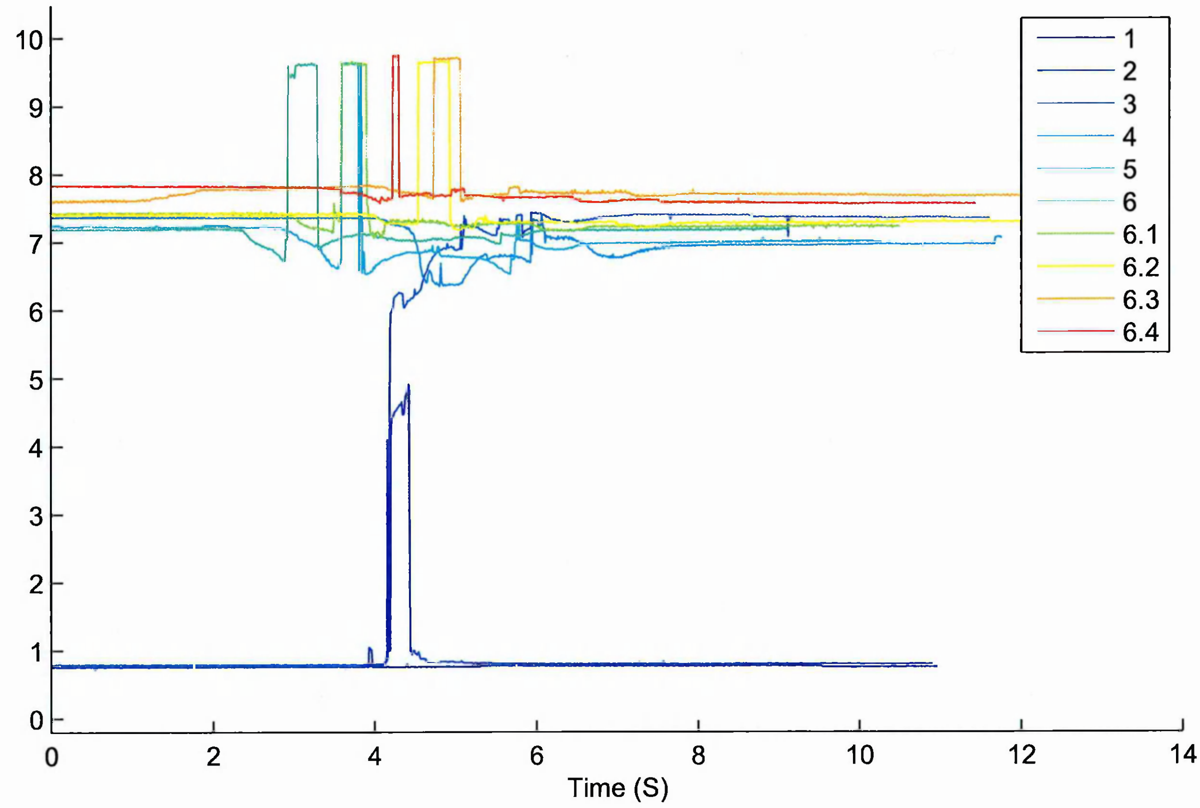
bone parallel top
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
Time (S)
1
2
3
4
5
6
6.1
6.2
6.3
6.4



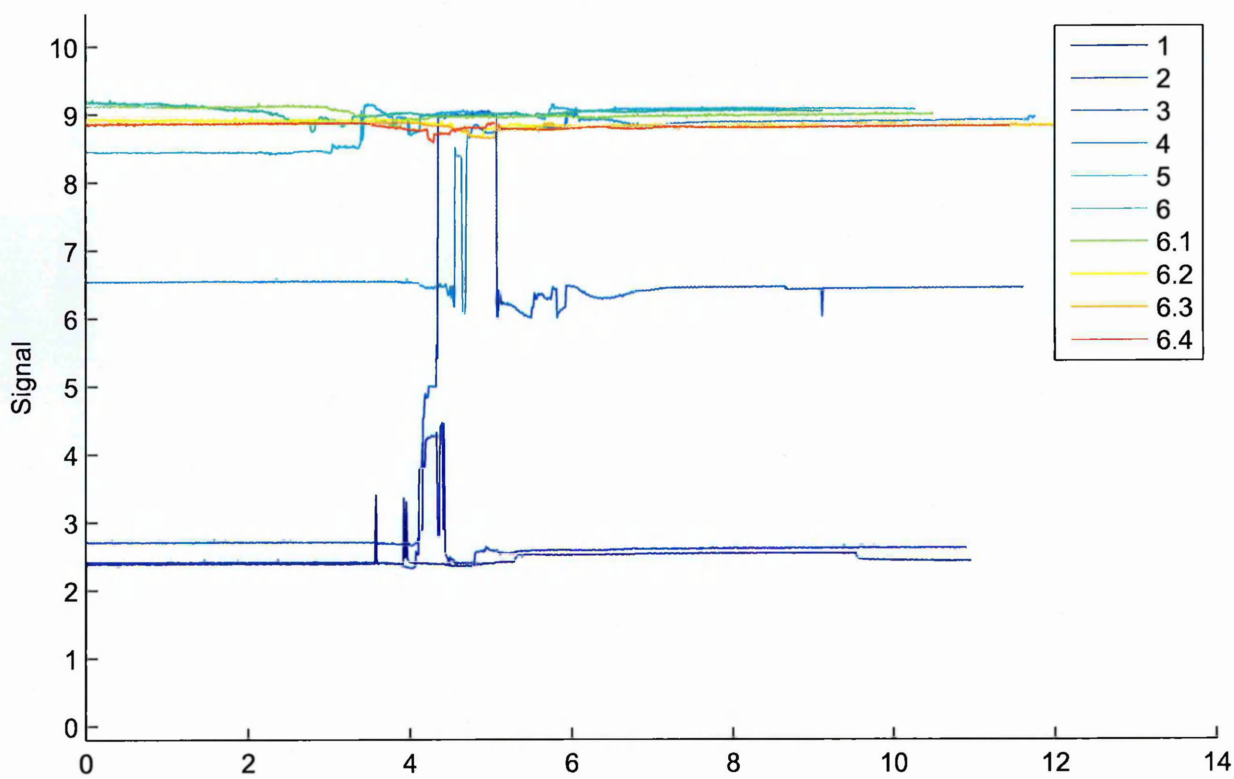
bone parallel bottom
Signal
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
1
2
3
4
5
6
6.1
6.2
6.3
6.4

Real3

flint beaker rim

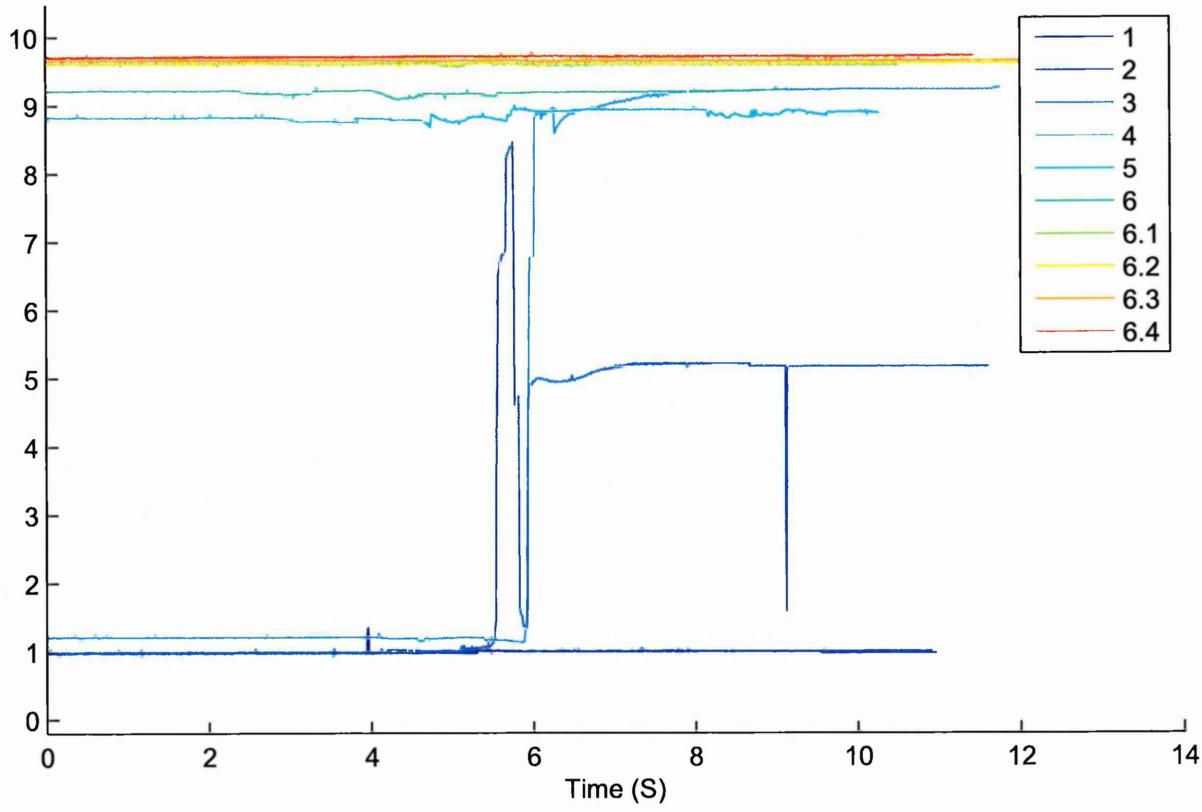


flint beaker body

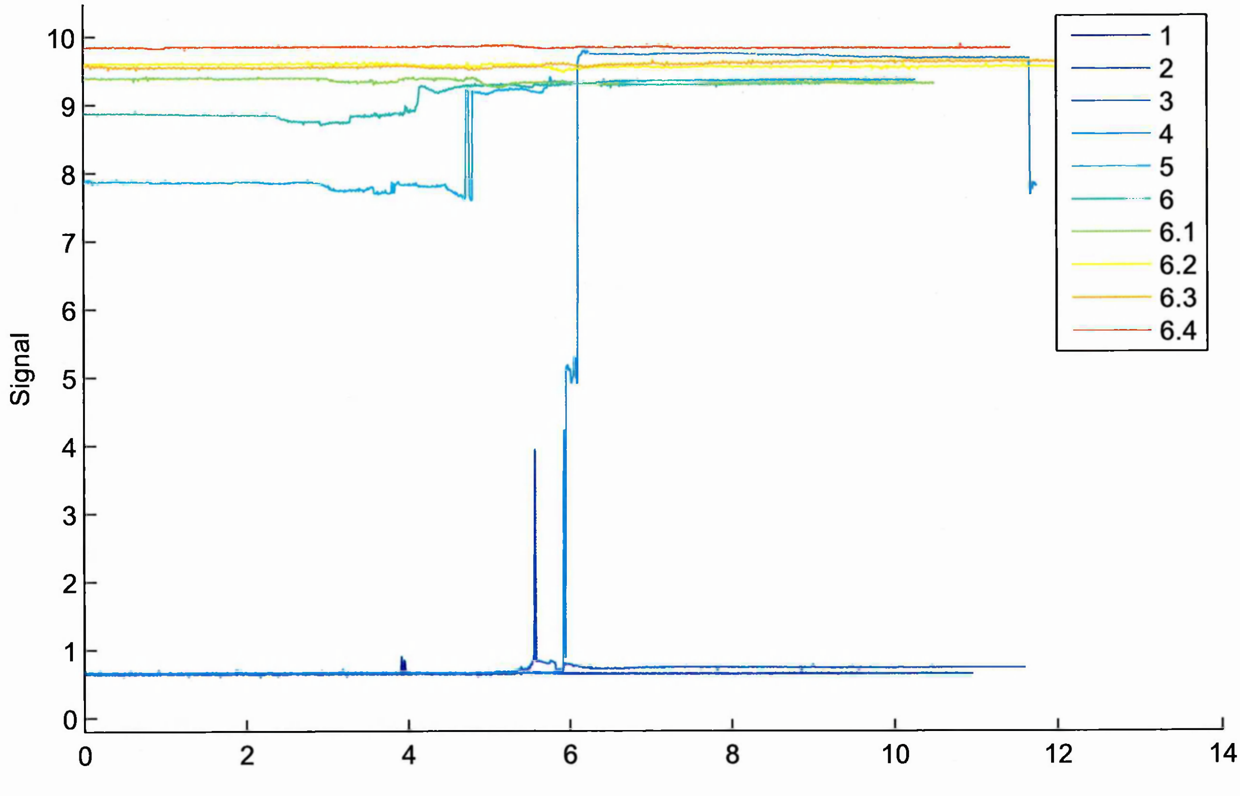


Real3

sand + flint tempered rim

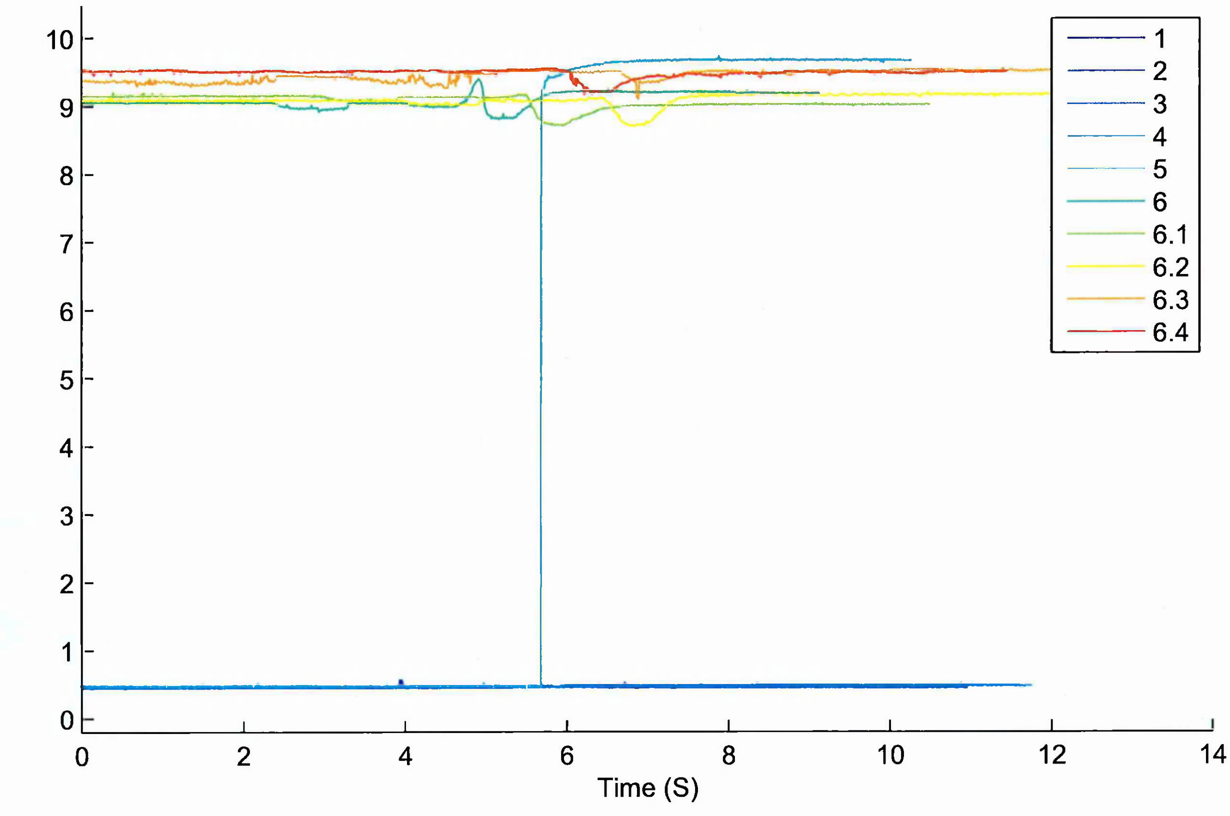


sand + flint tempered body

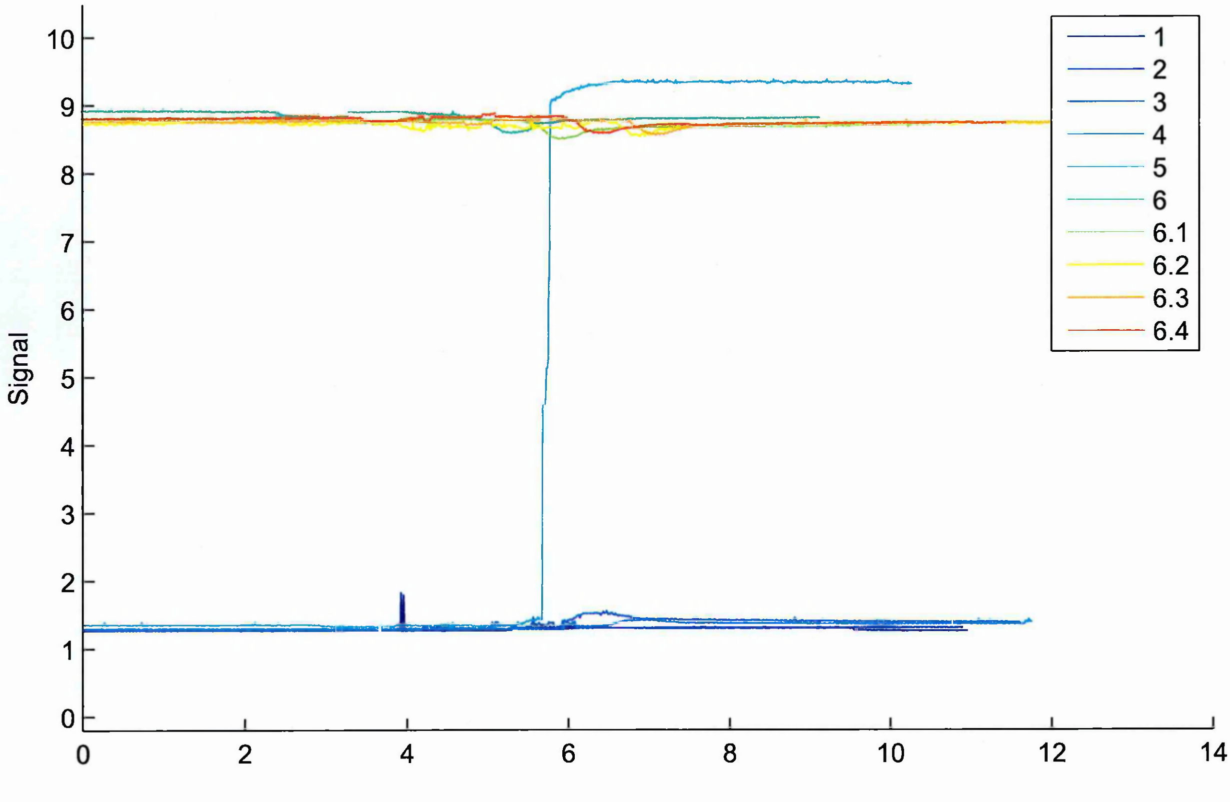


Real3

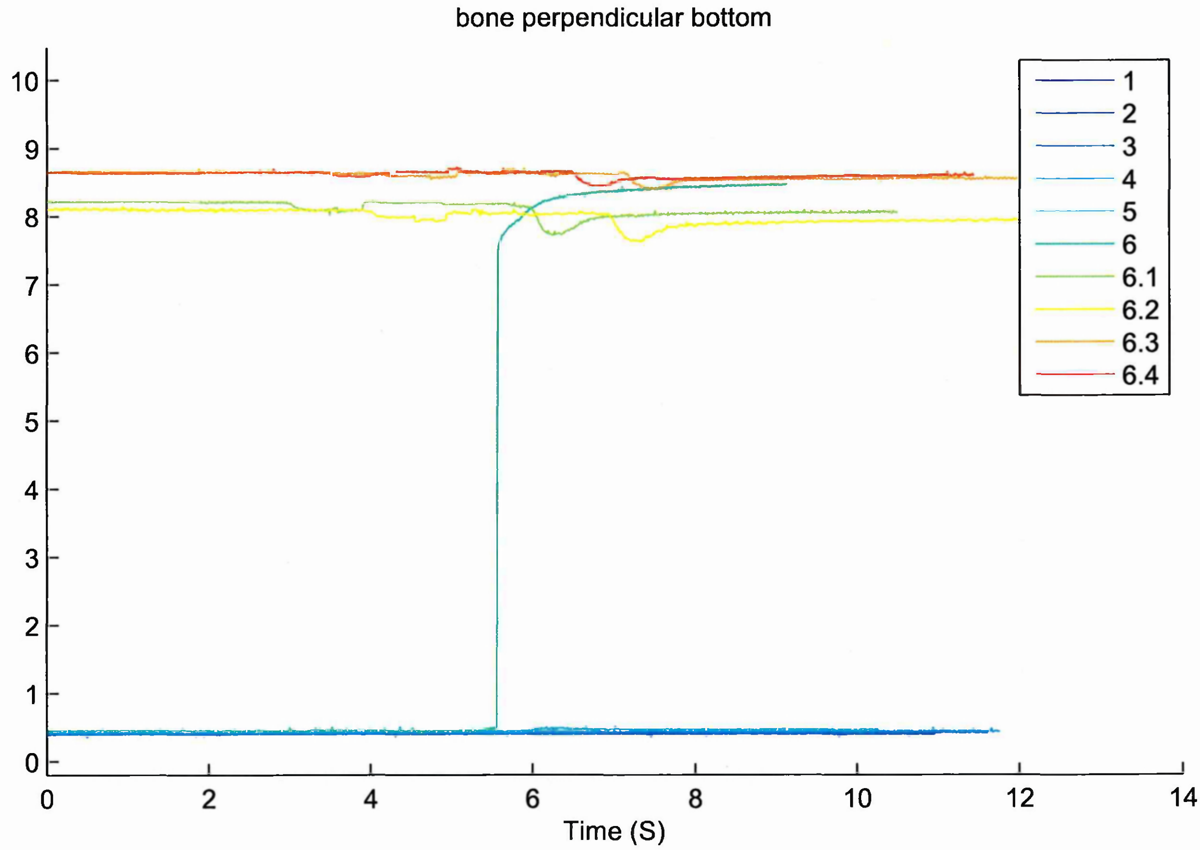
roman thrown rim

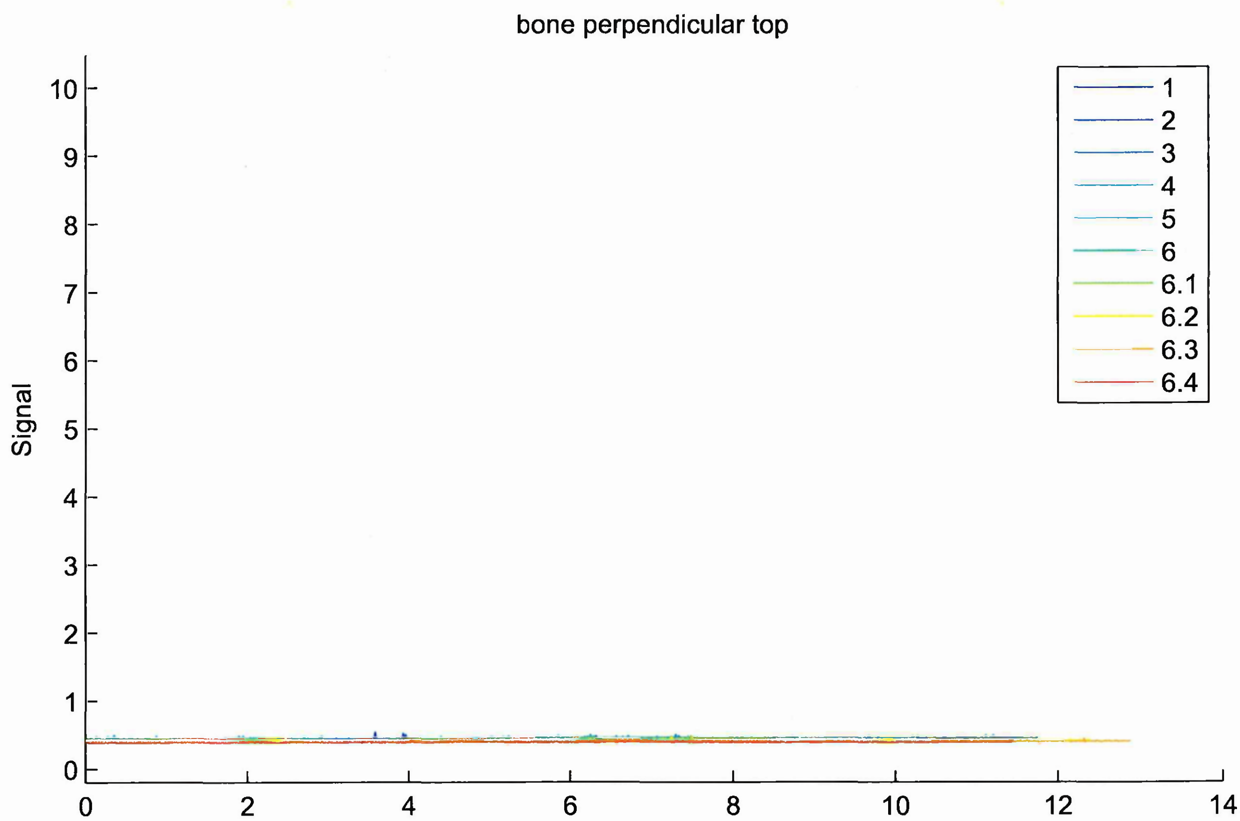


roman thrown body

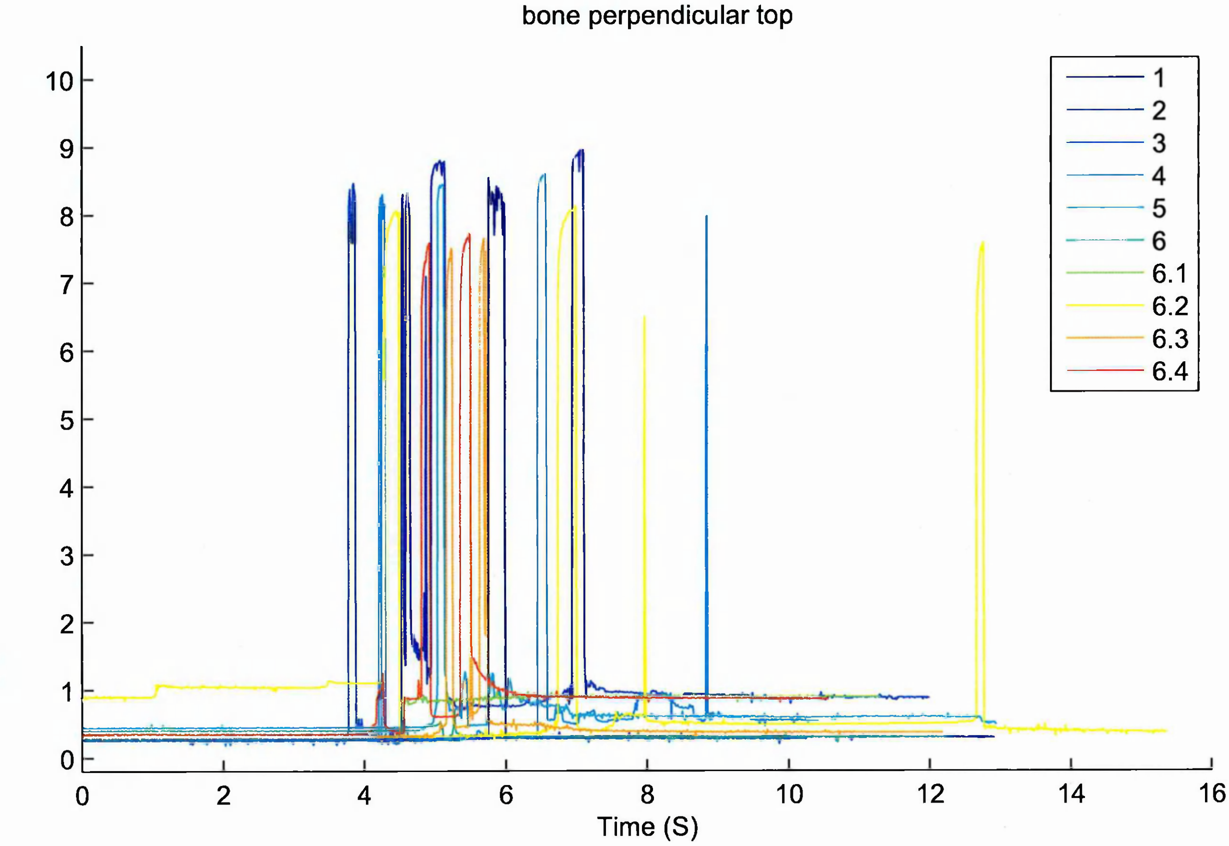


Real3

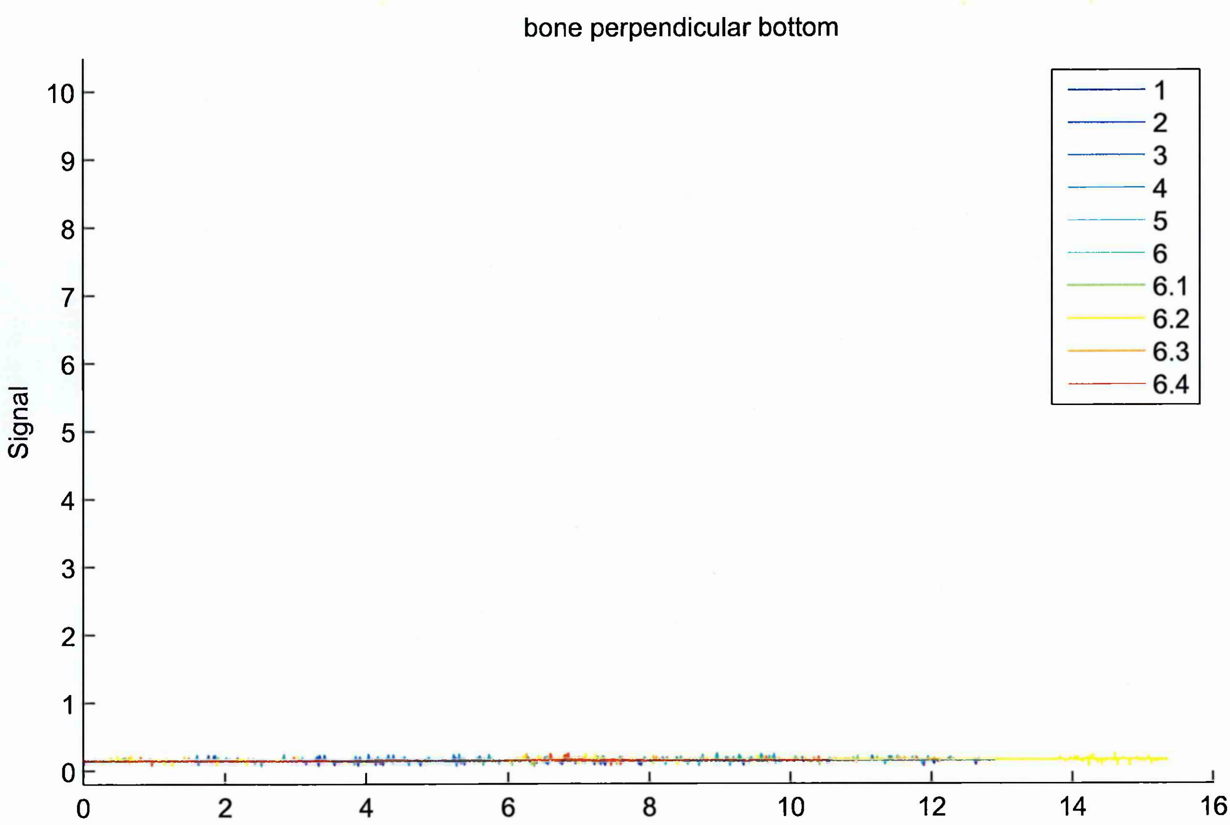

bone perpendicular bottom
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
Time (S)
1
2
3
4
5
6
6.1
6.2
6.3
6.4


bone perpendicular top
Signal
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
1
2
3
4
5
6
6.1
6.2
6.3
6.4

Real4

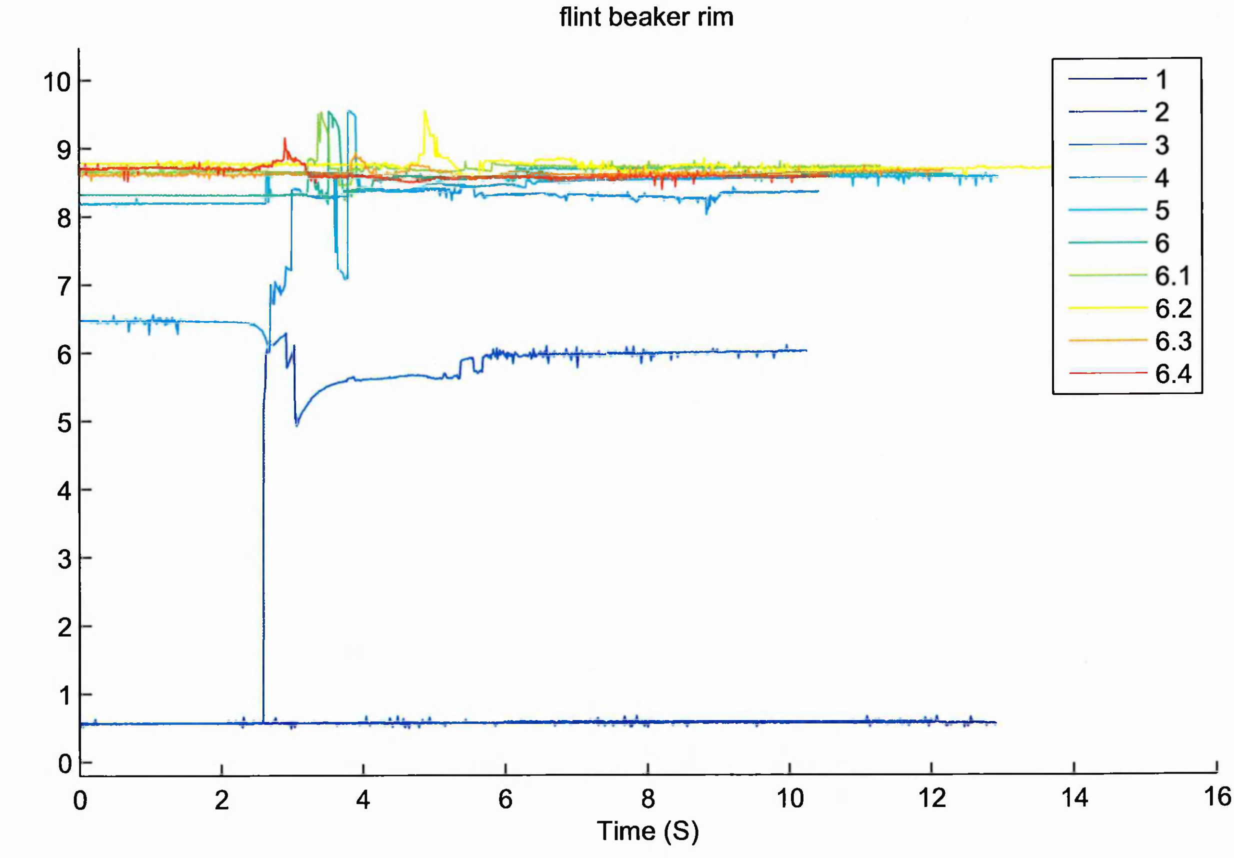


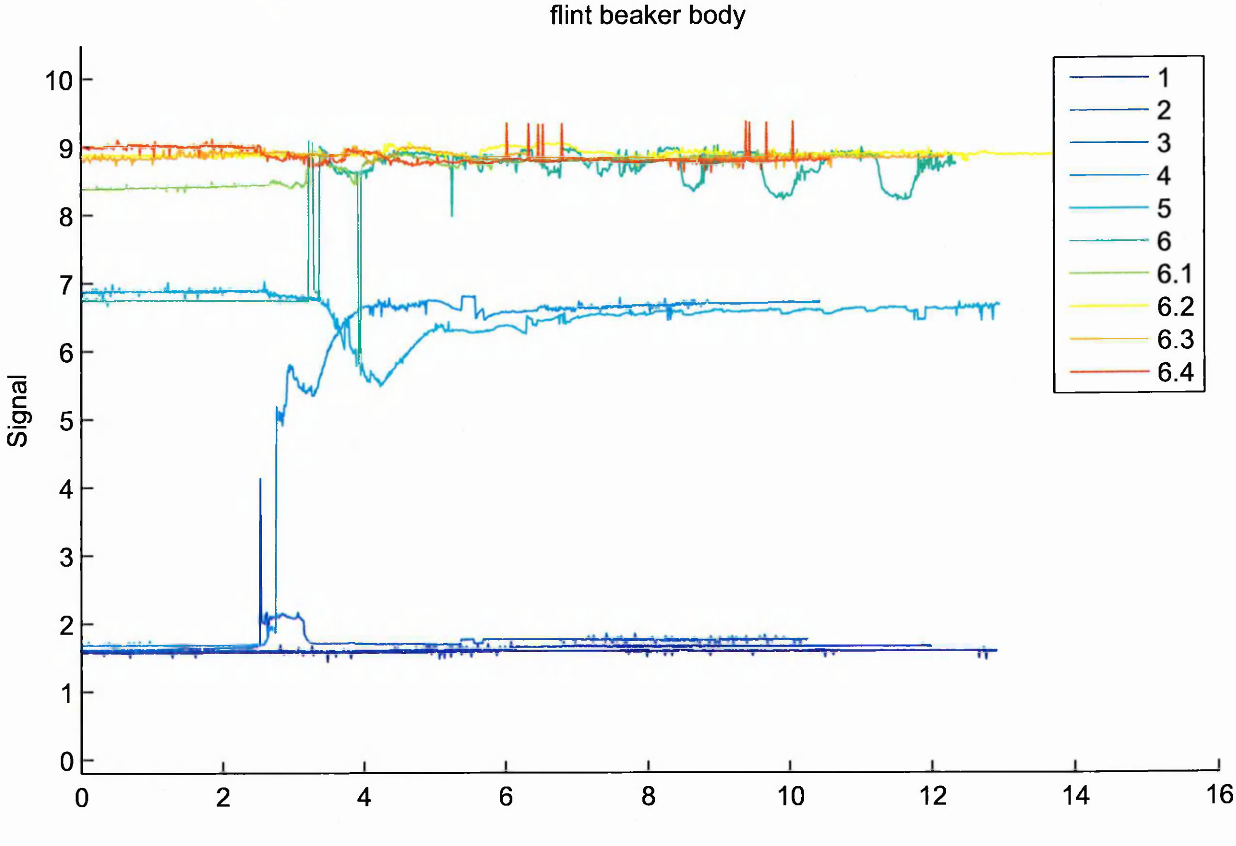
bone perpendicular top
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
16
Time (S)
1
2
3
4
5
6
6.1
6.2
6.3
6.4



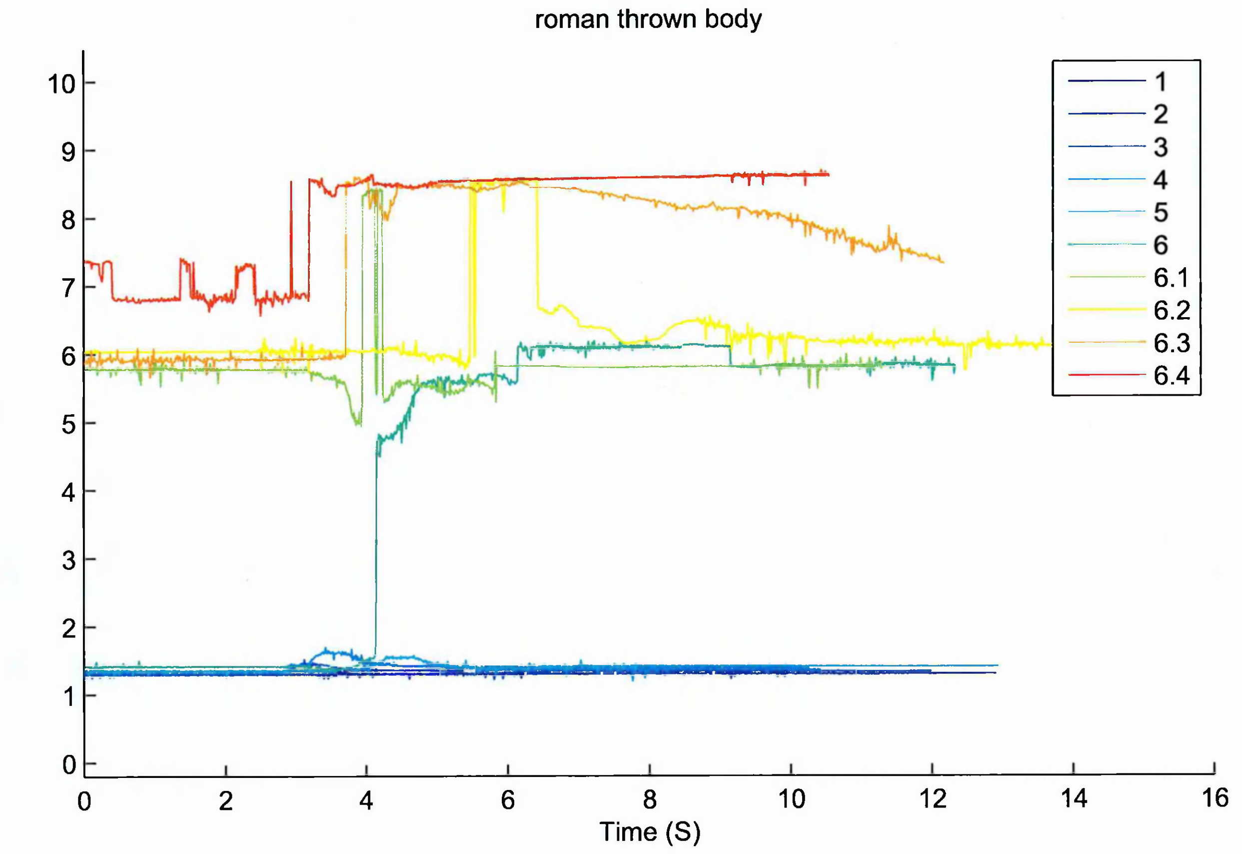
bone perpendicular bottom
Signal
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
16
1
2
3
4
5
6
6.1
6.2
6.3
6.4

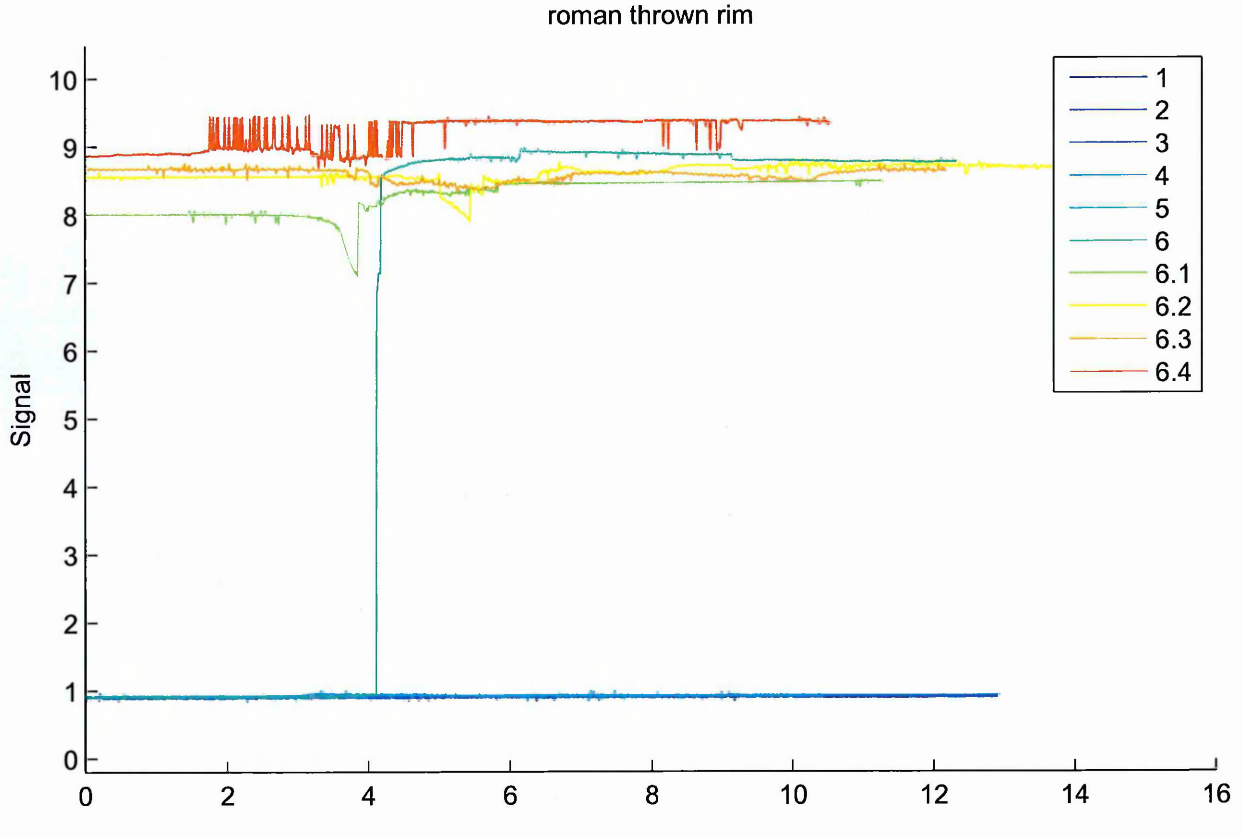
Real4


flint beaker rim
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
16
Time (S)
1
2
3
4
5
6
6.1
6.2
6.3
6.4

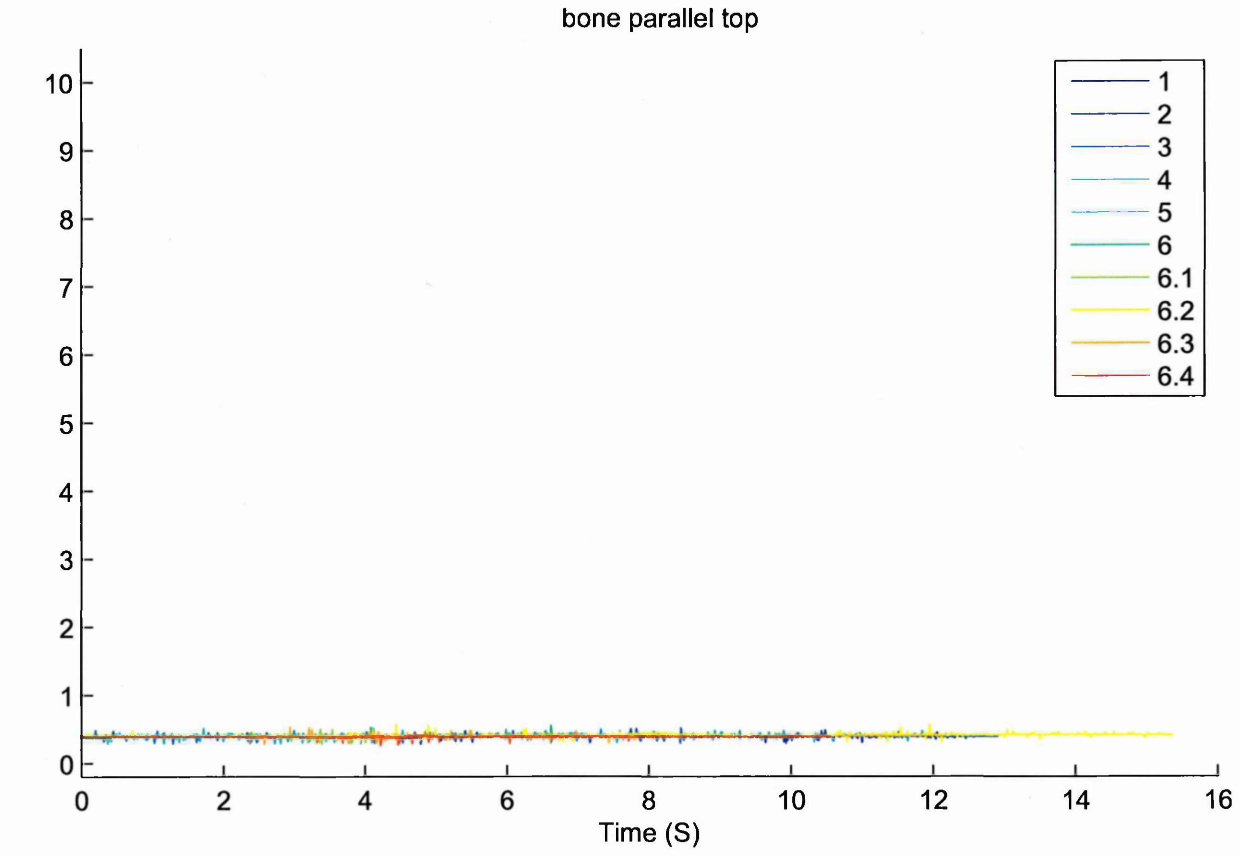

flint beaker body
Signal
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
16
1
2
3
4
5
6
6.1
6.2
6.3
6.4

Real4

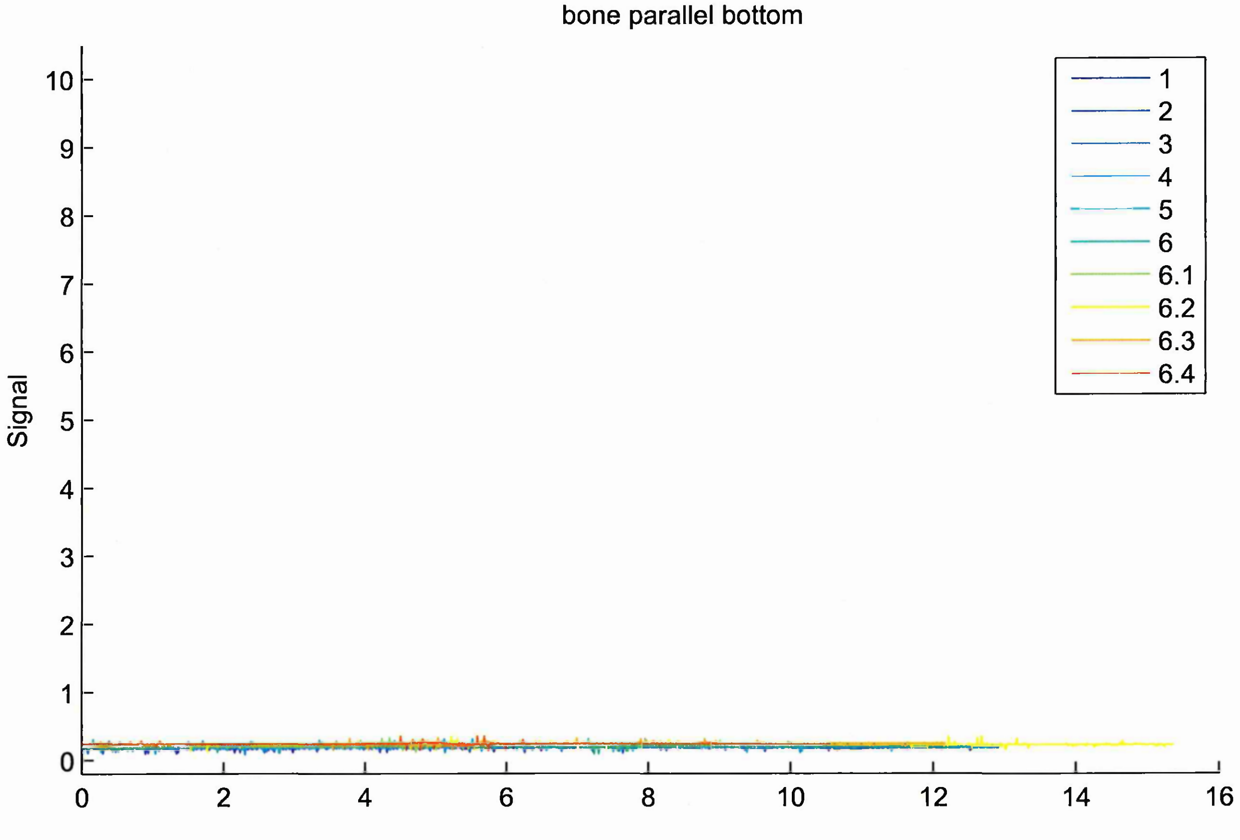

roman thrown body
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
16
Time (S)
1
2
3
4
5
6
6.1
6.2
6.3
6.4


roman thrown rim
Signal
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
16
1
2
3
4
5
6
6.1
6.2
6.3
6.4

Real4

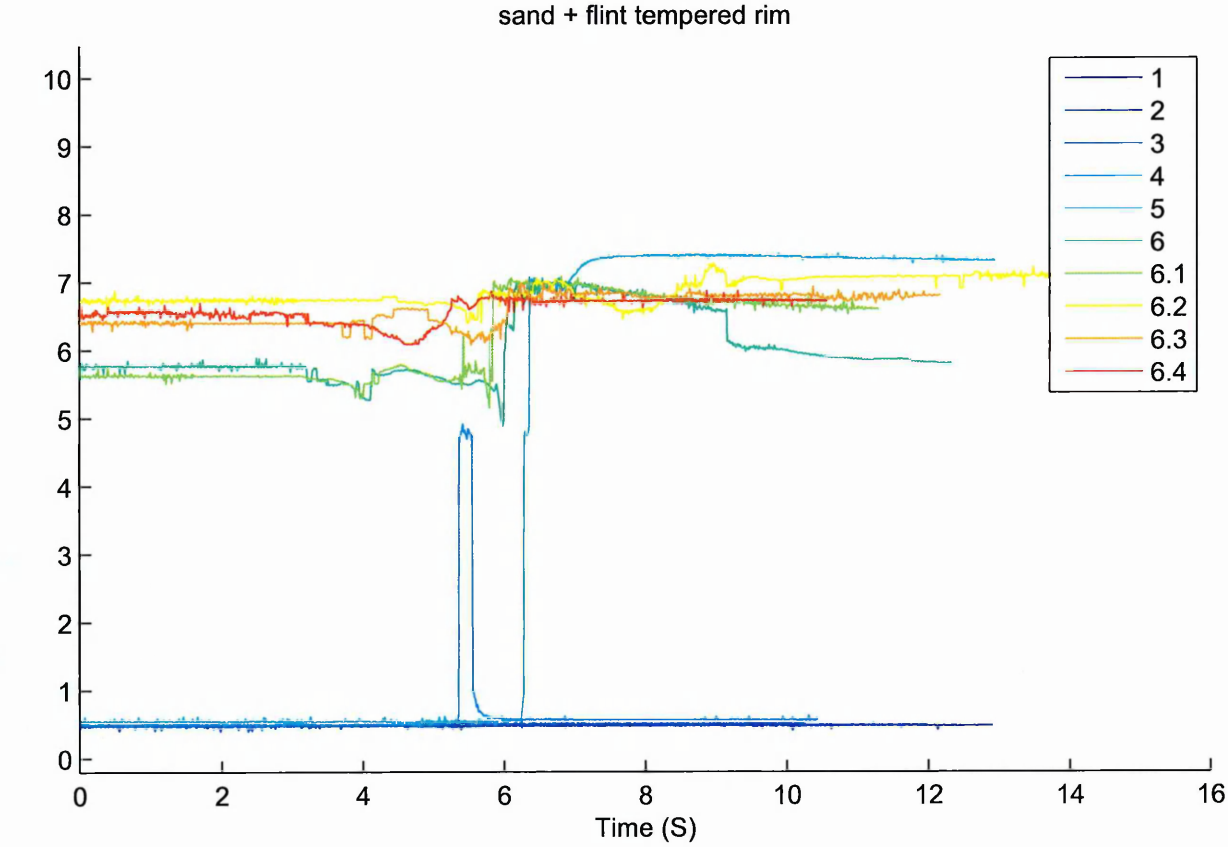


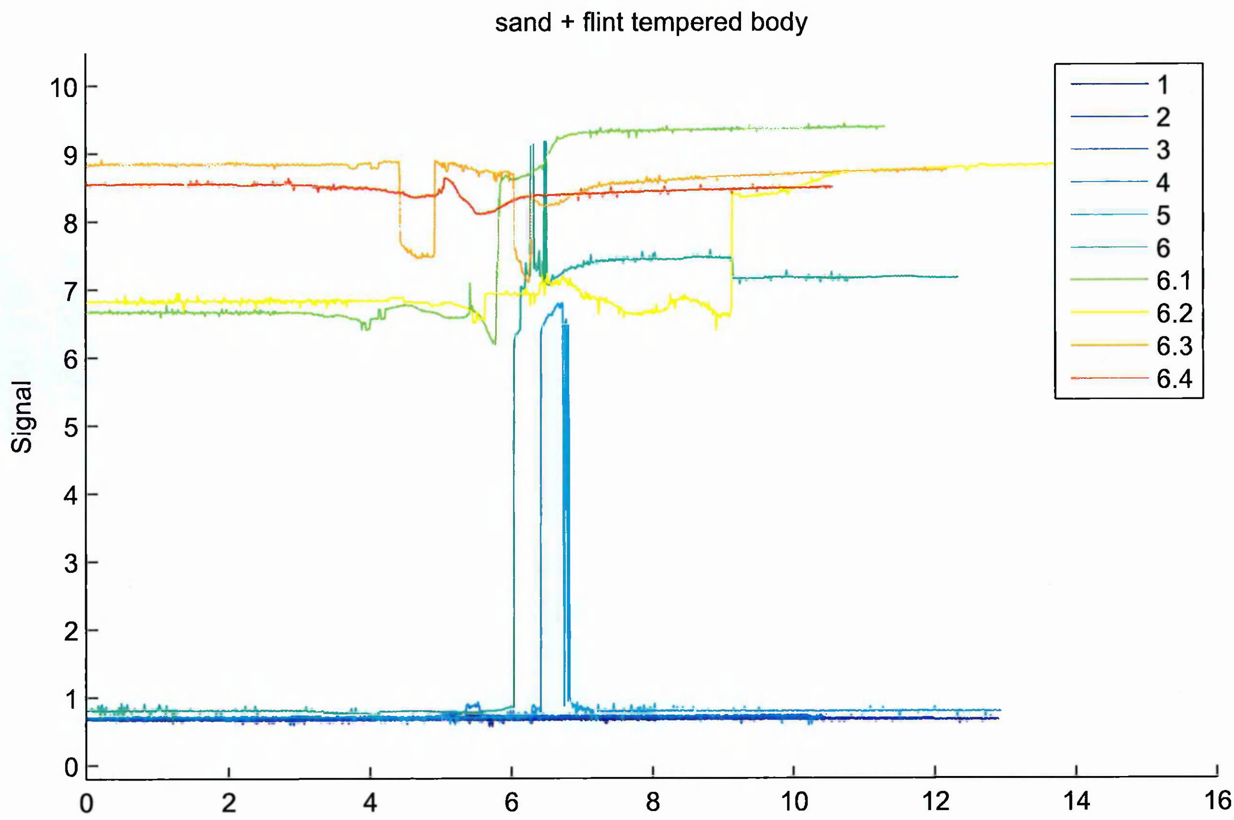
bone parallel top
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
16
Time (S)
1
2
3
4
5
6
6.1
6.2
6.3
6.4



bone parallel bottom
Signal
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
16
1
2
3
4
5
6
6.1
6.2
6.3
6.4

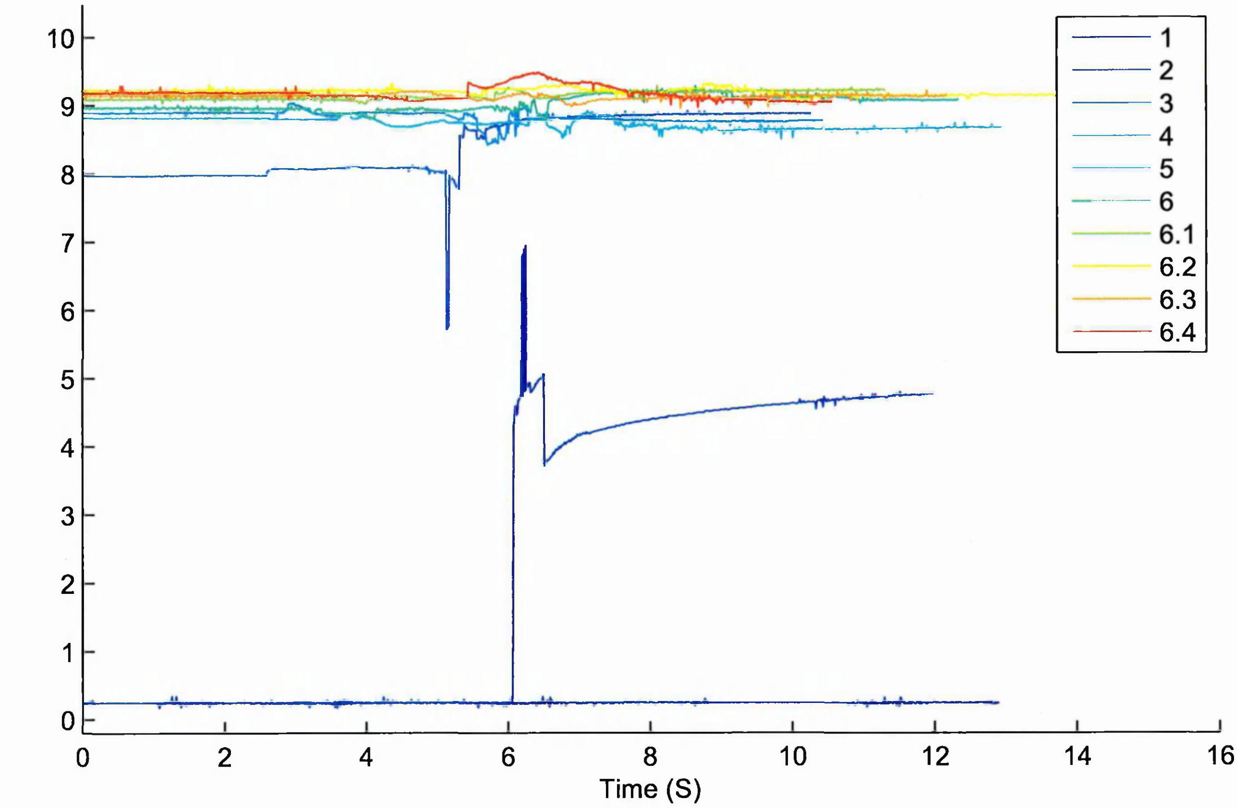
Real4


sand + flint tempered rim
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
16
Time (S)
1
2
3
4
5
6
6.1
6.2
6.3
6.4

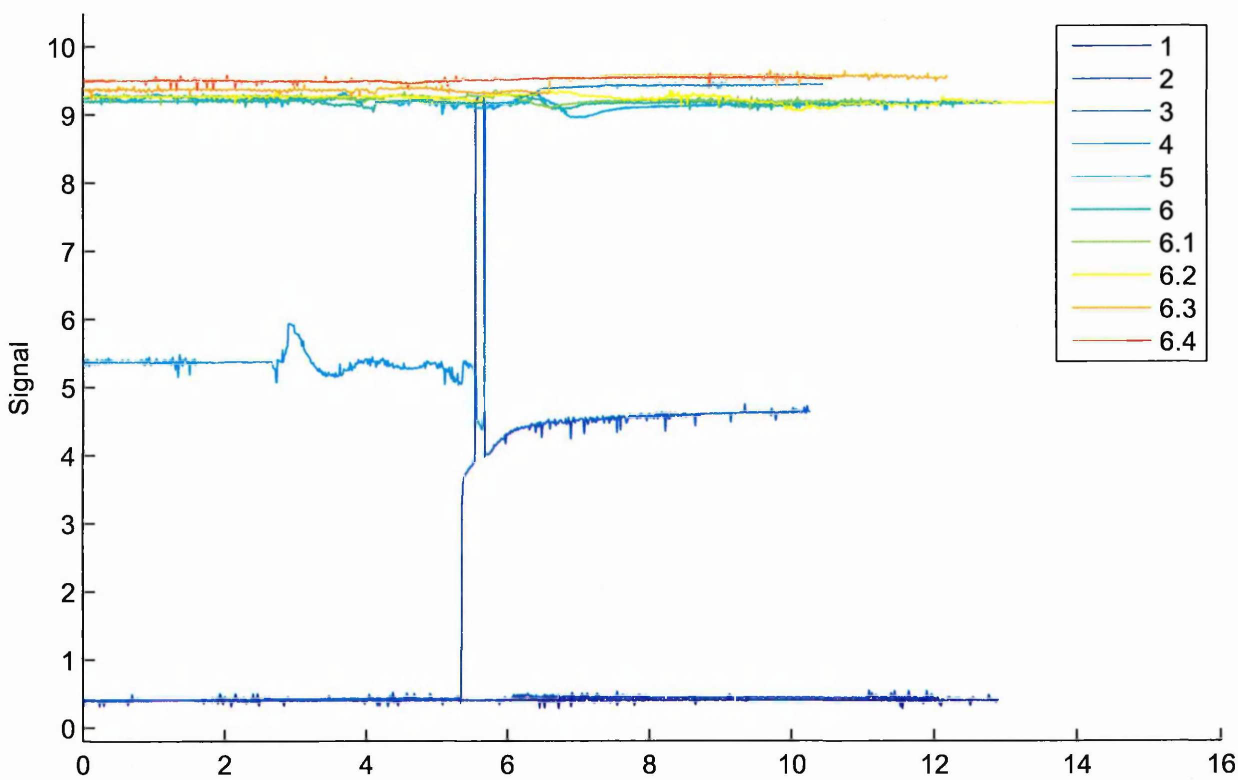

sand + flint tempered body
Signal
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
16
1
2
3
4
5
6
6.1
6.2
6.3
6.4

Real4

shell tempered rim

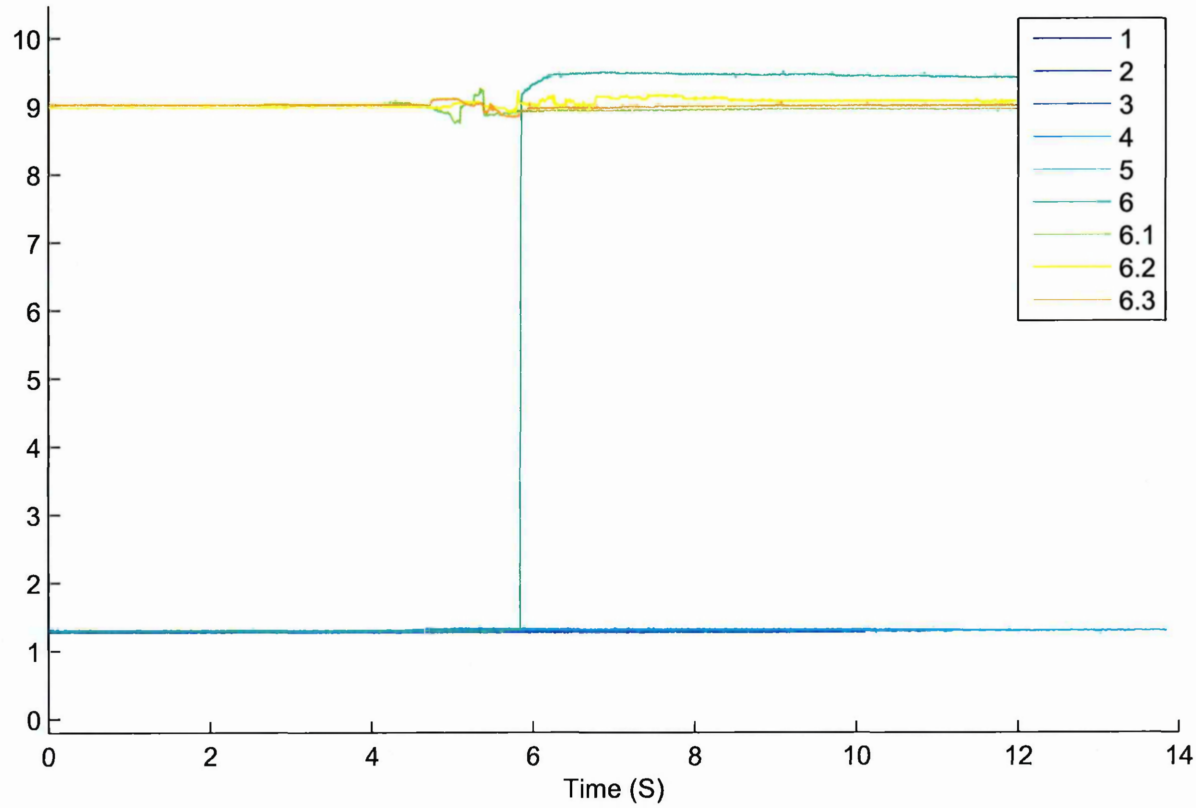


shell tempered body

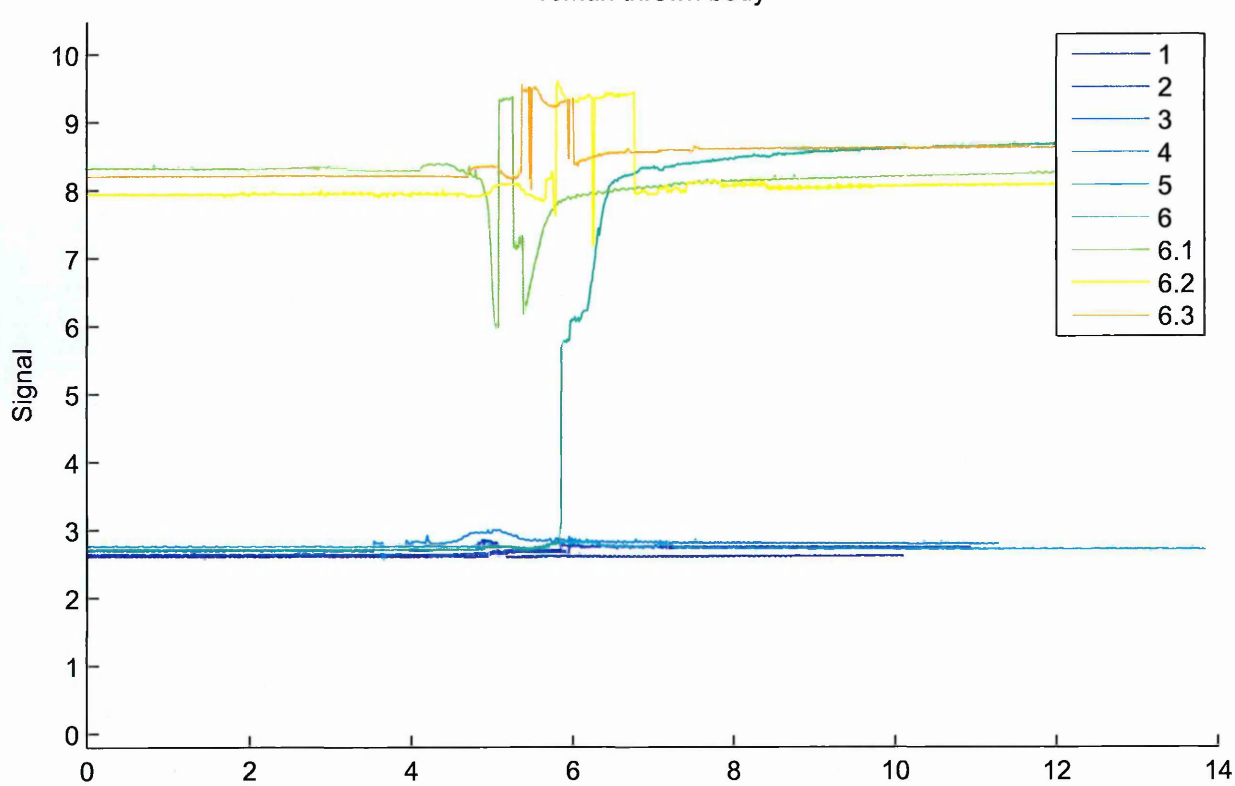


Real5

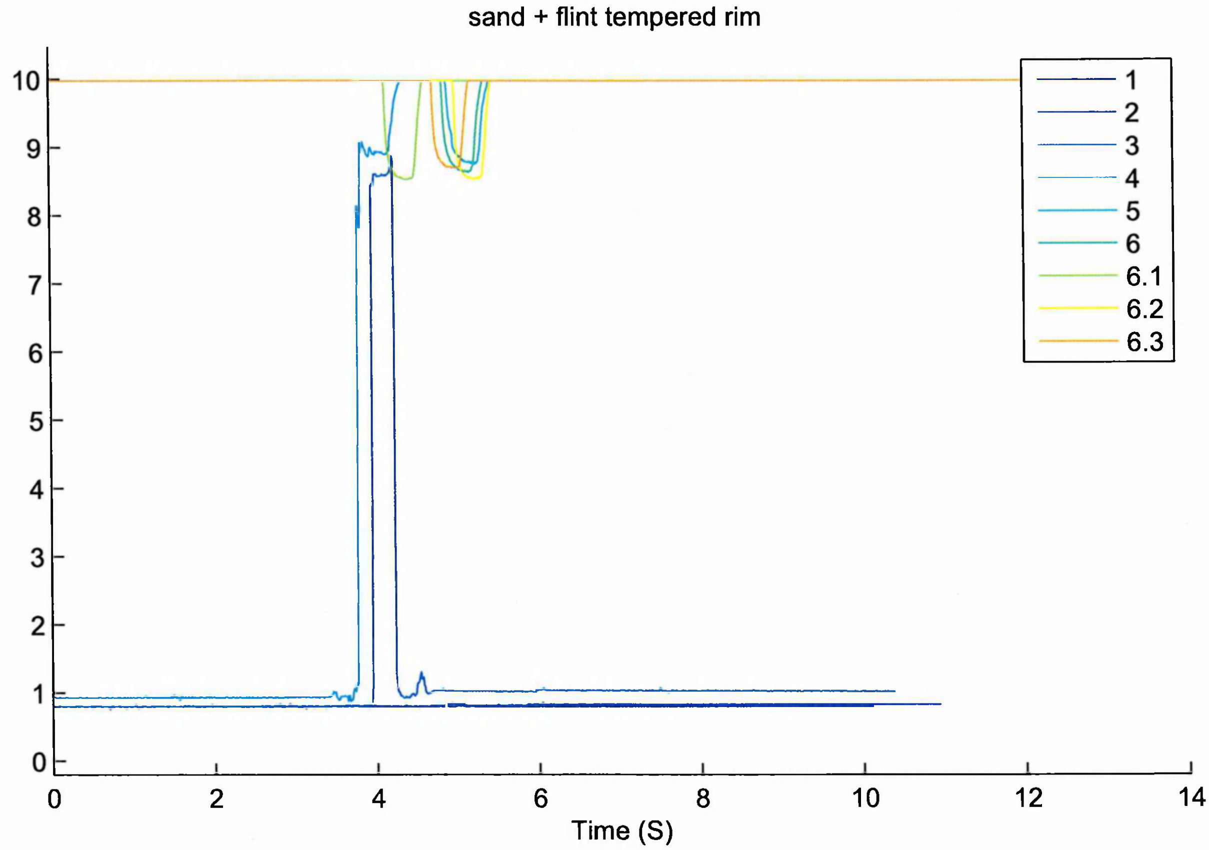
roman thrown rim



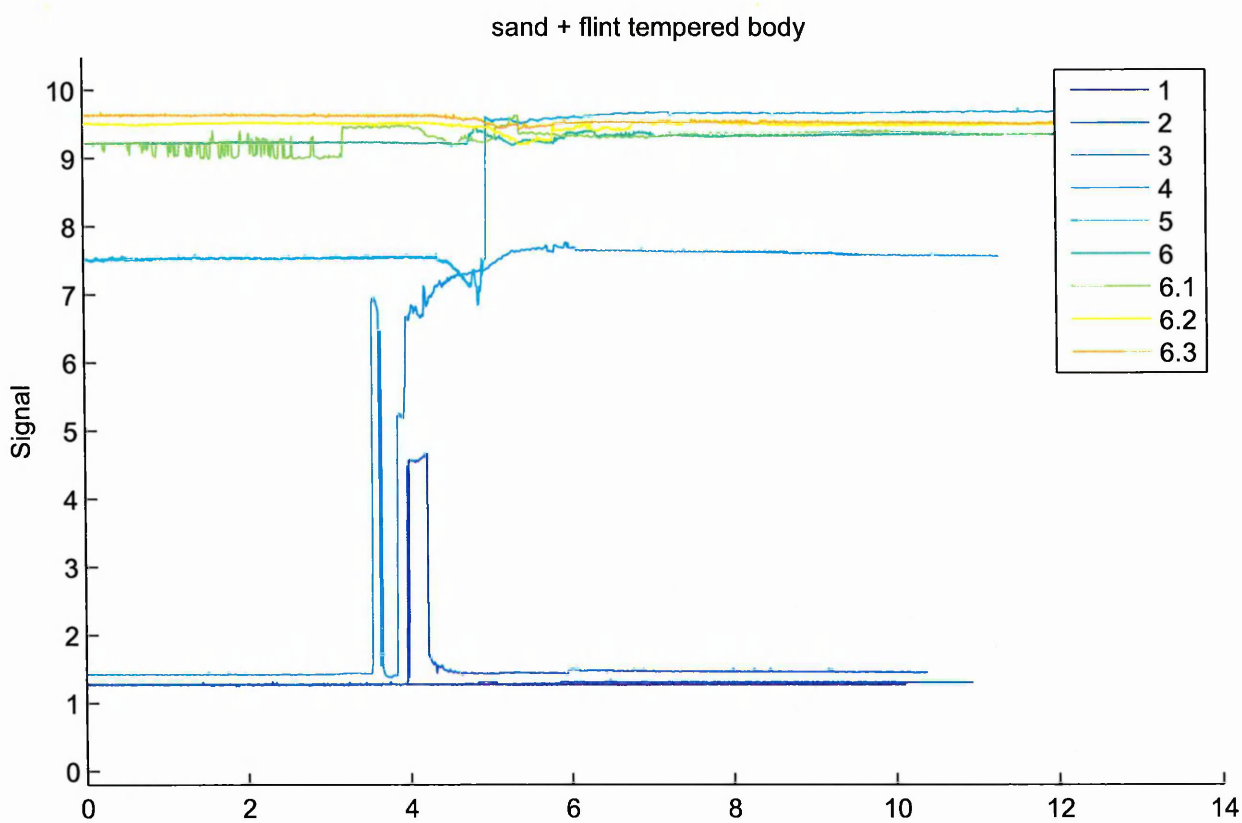
roman thrown body



Real5



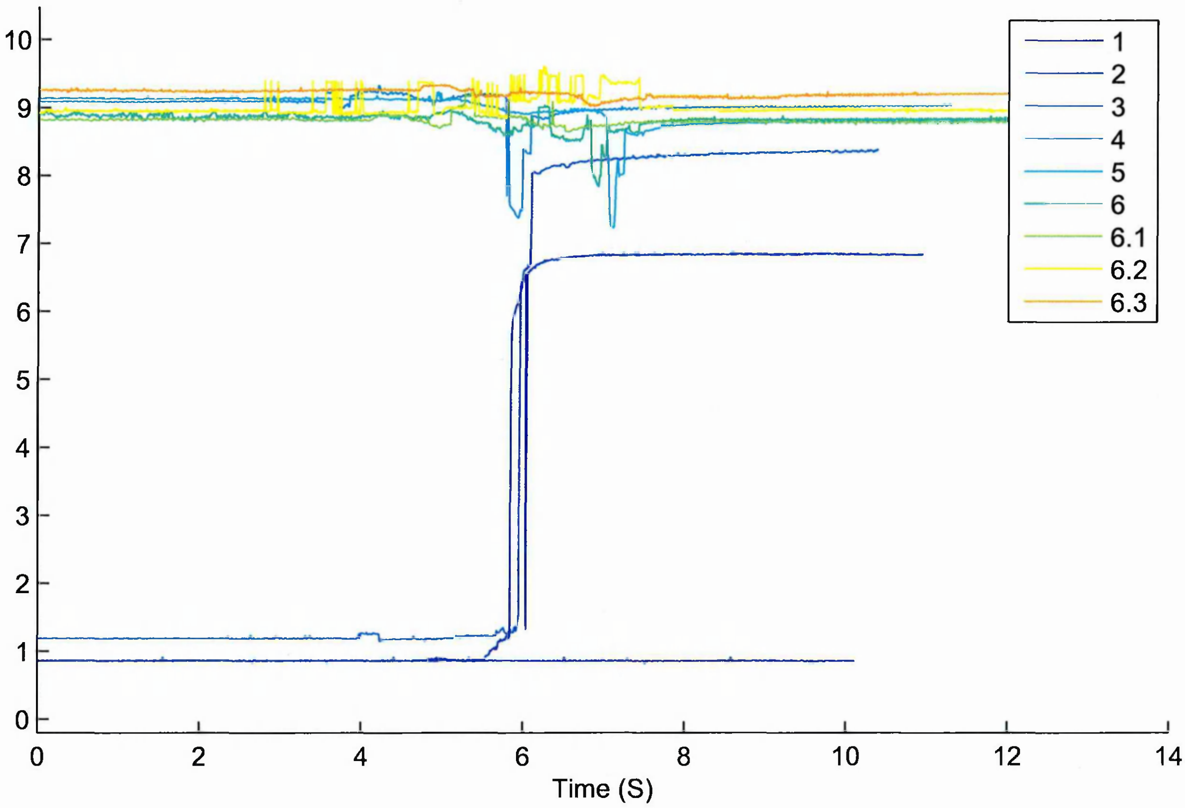
sand + flint tempered rim
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
Time (S)
1
2
3
4
5
6
6.1
6.2
6.3



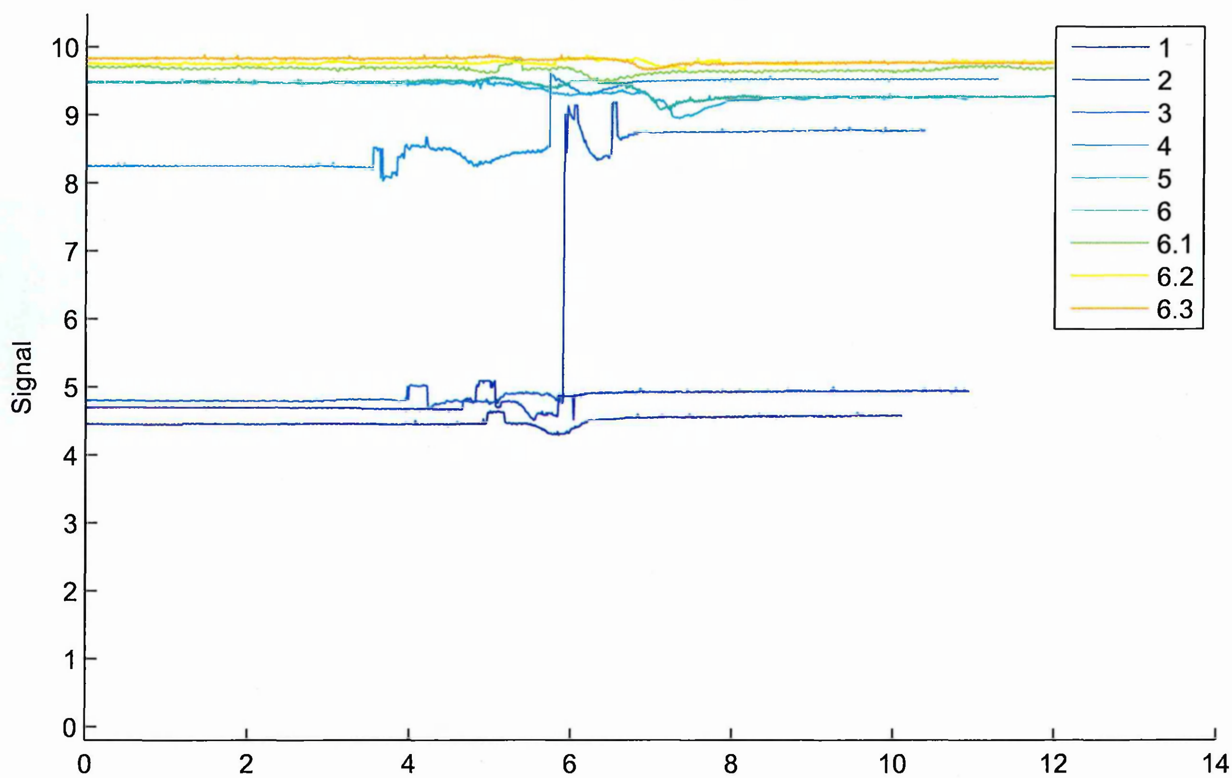
sand + flint tempered body
Signal
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
1
2
3
4
5
6
6.1
6.2
6.3

Real5

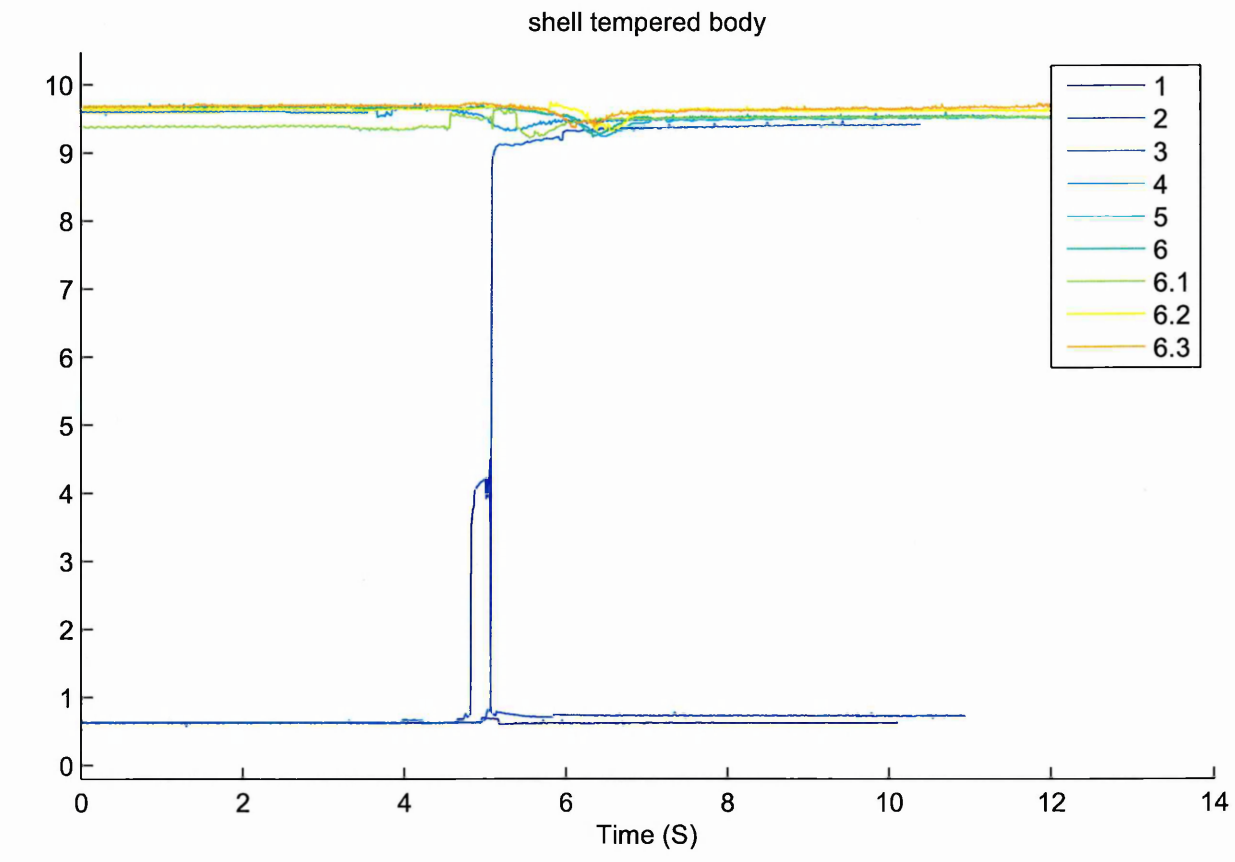
flint beaker rim



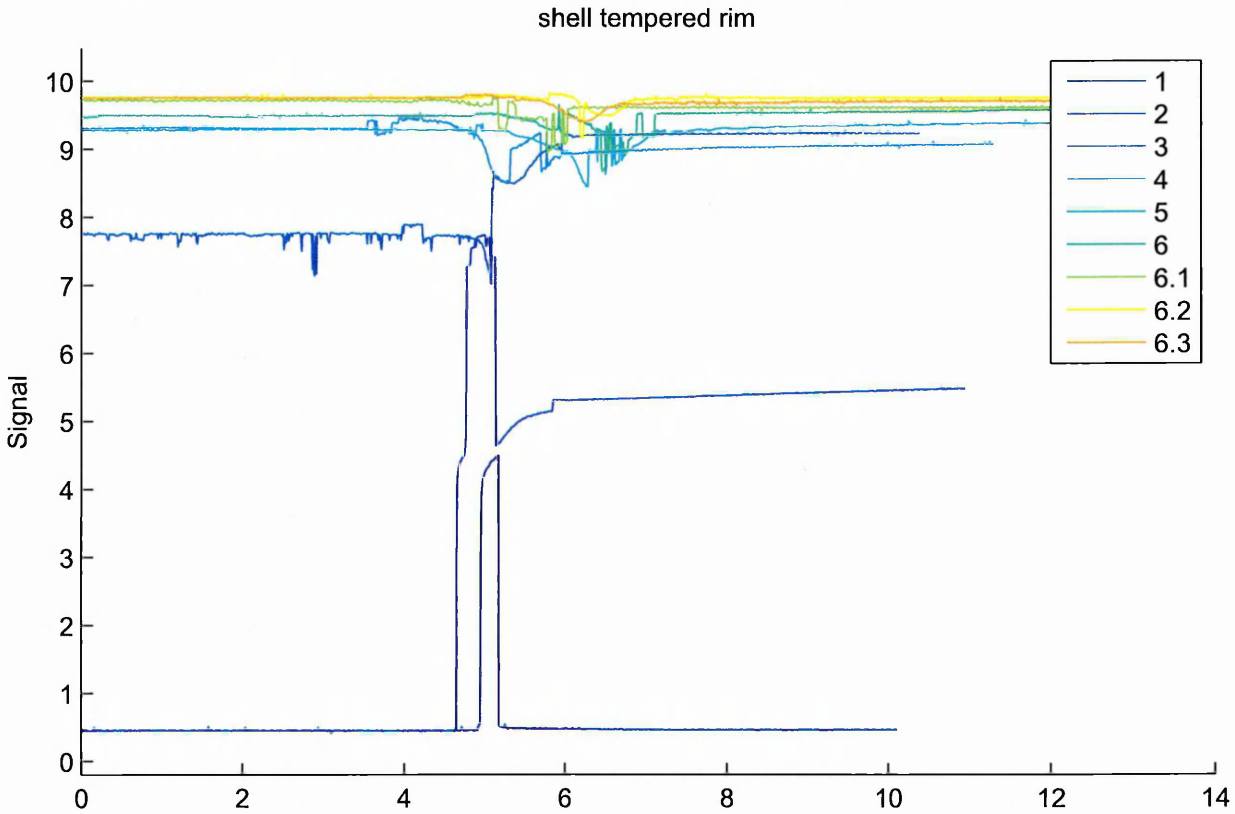
flint beaker body



Real5



shell tempered body
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
Time (S)
1
2
3
4
5
6
6.1
6.2
6.3



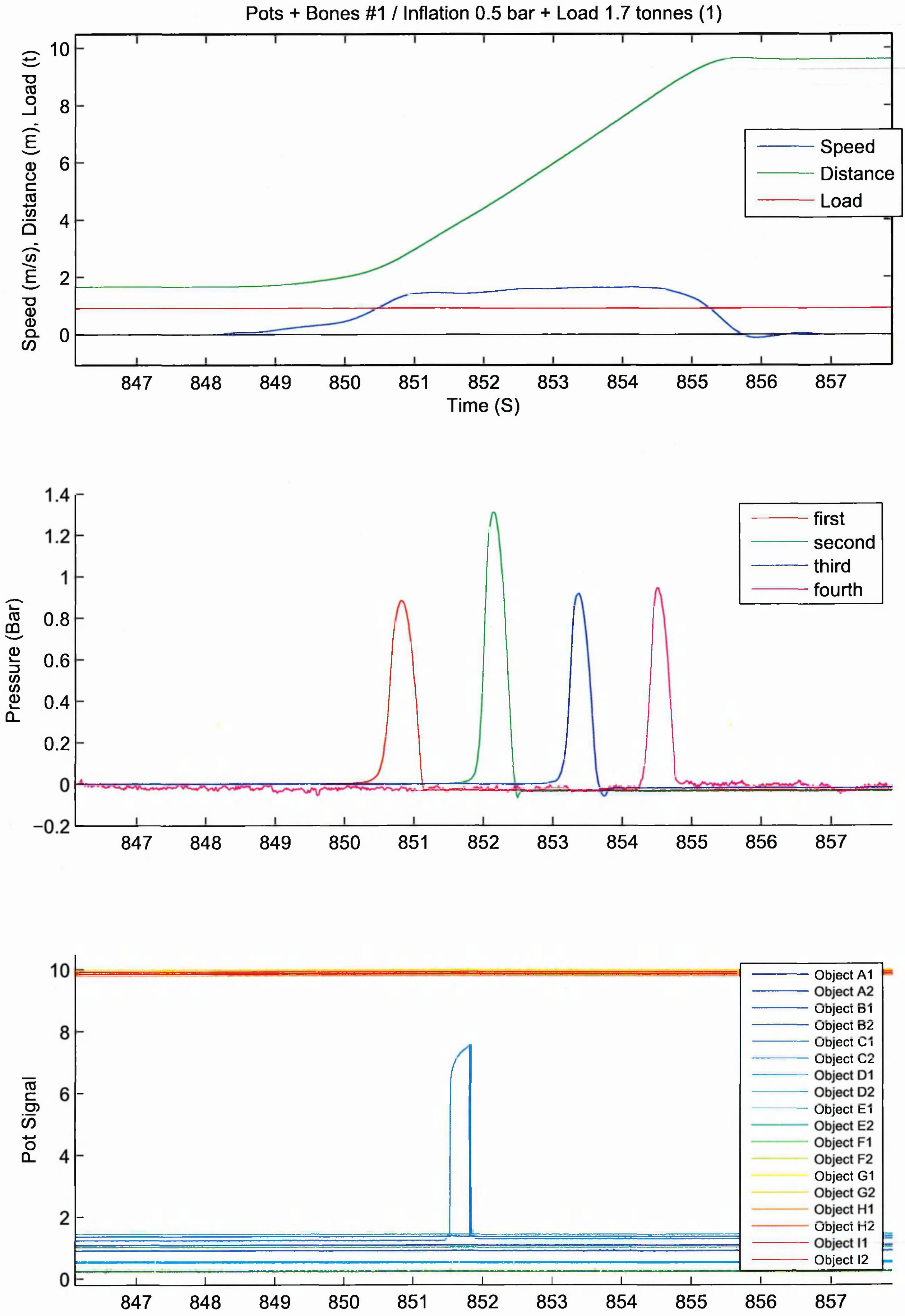
shell tempered rim
Signal
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
1
2
3
4
5
6
6.1
6.2
6.3

Appendix K: Visual presentation – Lab data organized by 'trial run'

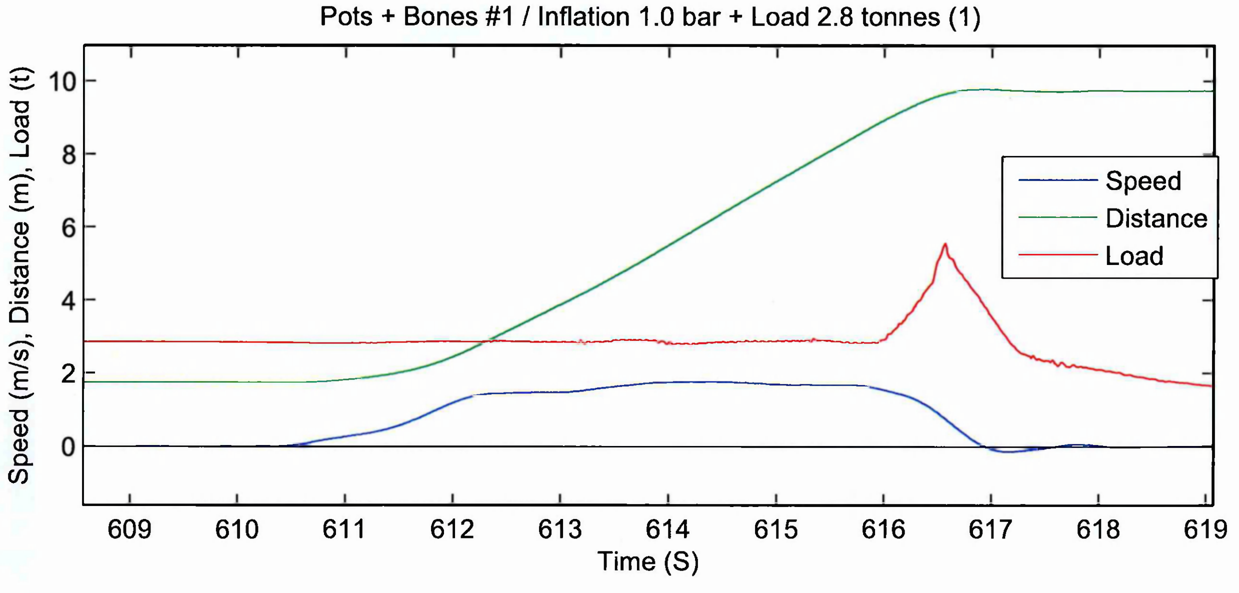
The following 54 pages show a second visual presentation approach for the data recorded during the laboratory soil bin breakage trials.

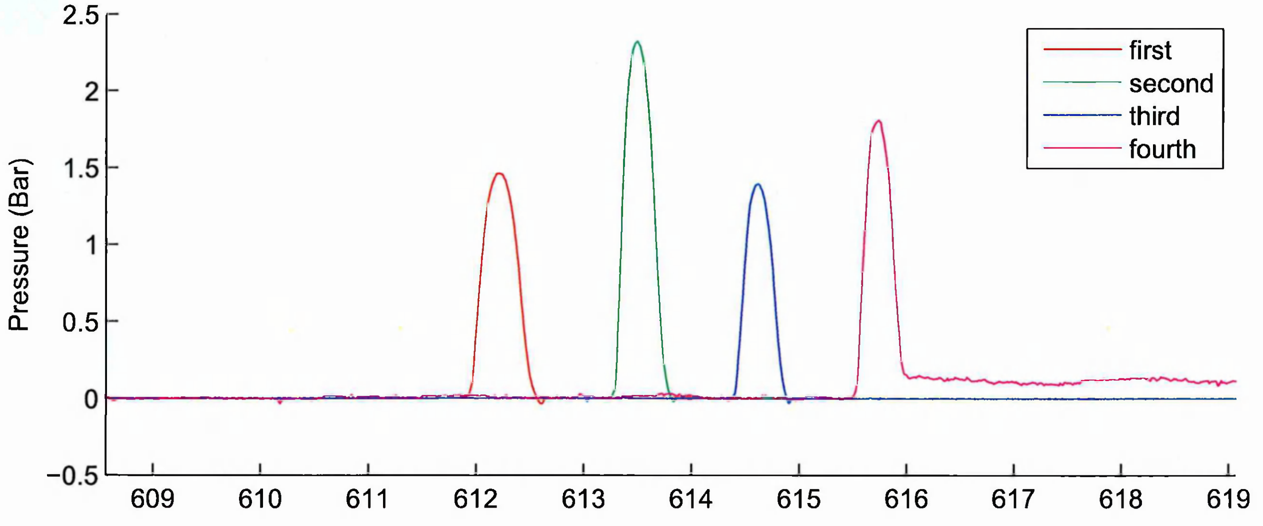
These pages show the electrical signals of the buried objects organized by run (as opposed to by object as in Appendix J). The buried pressure sensor outputs are also included in an accompanying graph, as are the recordings of the applied load on the tyre, and its velocity as it passed over the pressure sensors and buried objects. The breakage indication method is the same in these graphs as in Appendix J; it is just that the objects and their breakage are organized differently to provide another perspective for the visual breakage analysis.

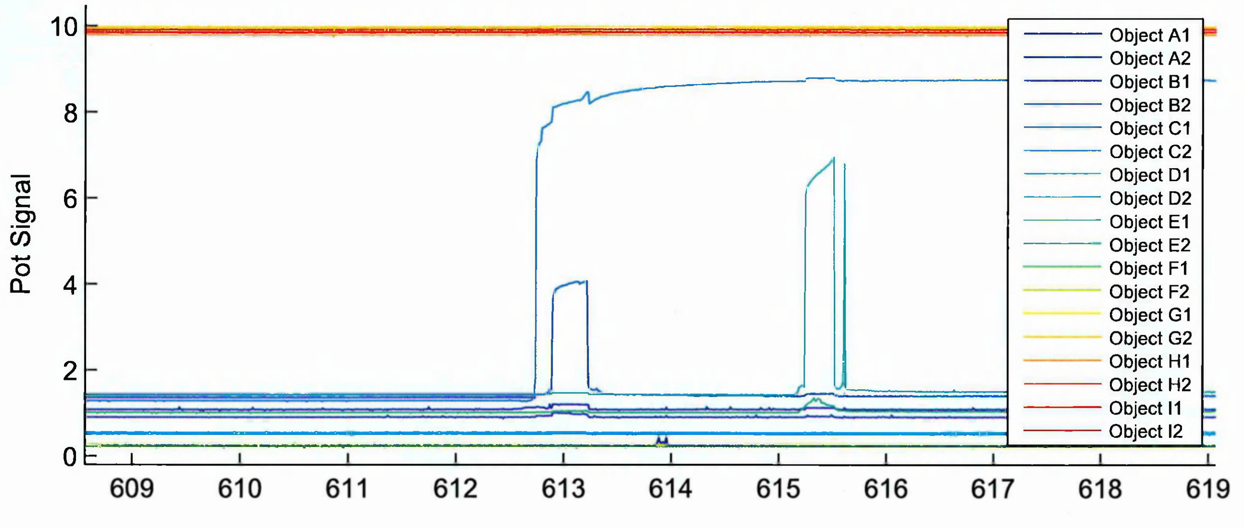
R1	R1
Object A1	bone parallel top
Object A2	bone parallel bottom
Object B1	sand + flint tempered rim
Object B2	sand + flint tempered body
Object C1	shell tempered body
Object C2	shell tempered rim
Object D1	roman thrown rim
Object D2	roman thrown body
Object E1	flint beaker rim
Object E2	flint beaker body
Object F1	bone perpendicular bottom
Object F2	bone perpendicular top
Object G1	X
Object G2	X
Object H1	X
Object H2	X
Object I1	X
Object I2	X

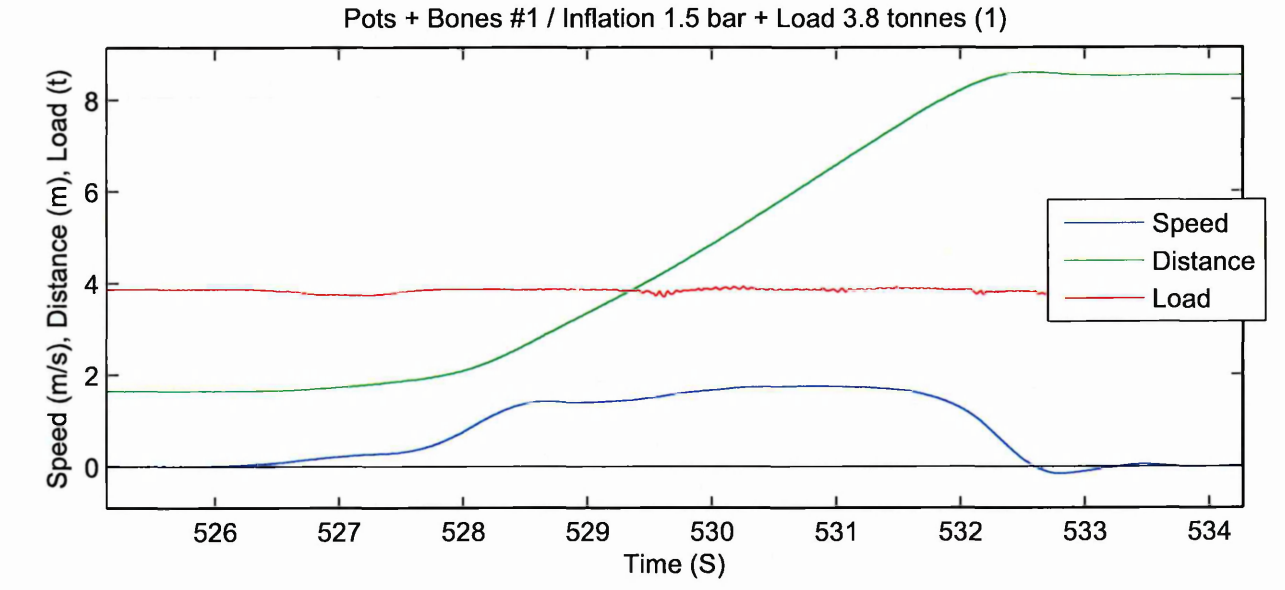


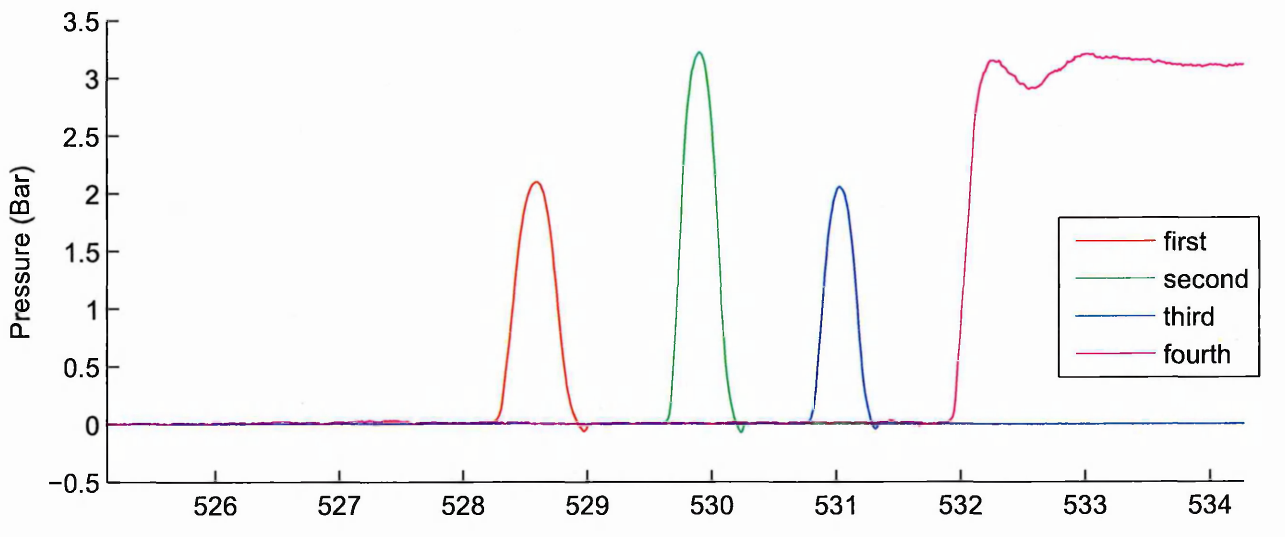
Pots + Bones #1 / Inflation 0.5 bar + Load 1.7 tonnes (1)
Speed (m/s), Distance (m), Load (t)
Speed
Distance
Load
Time (S)
Pressure (Bar)
first
second
third
fourth
Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2

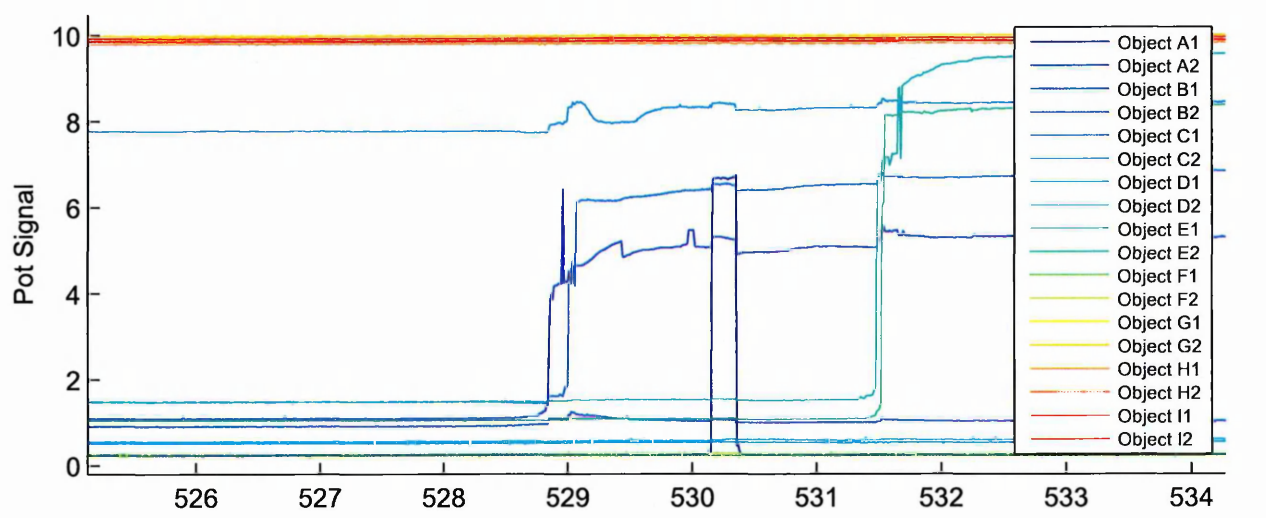

Pots + Bones #1 / Inflation 1.0 bar + Load 2.8 tonnes (1)
Speed (m/s), Distance (m), Load (t)
Speed
Distance
Load
Time (S)

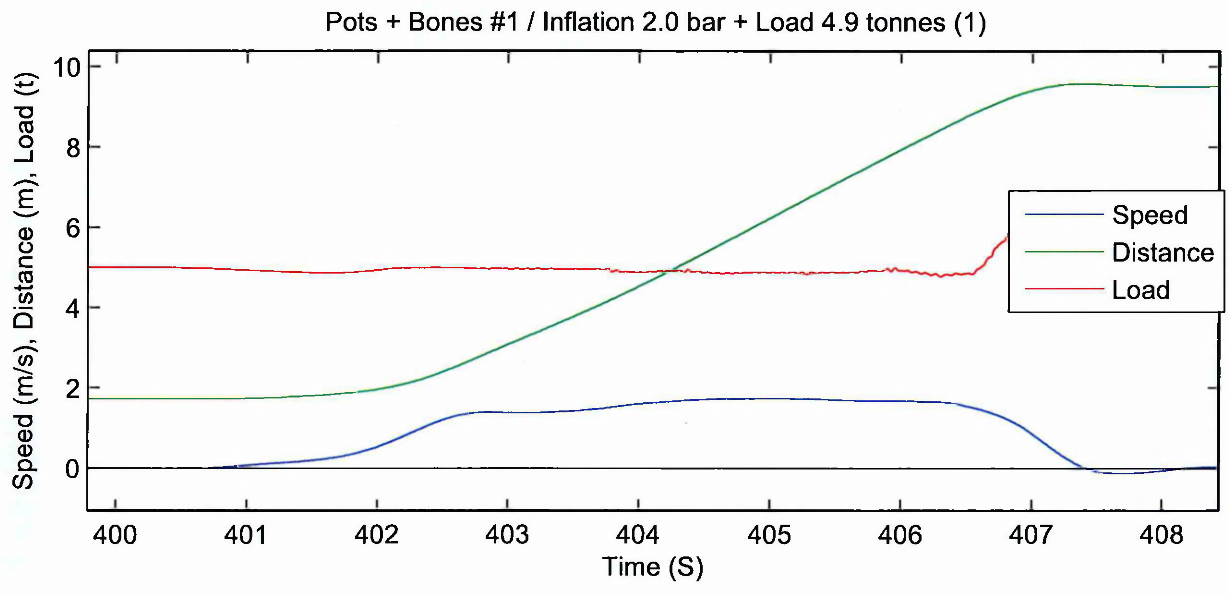

Pressure (Bar)
first
second
third
fourth

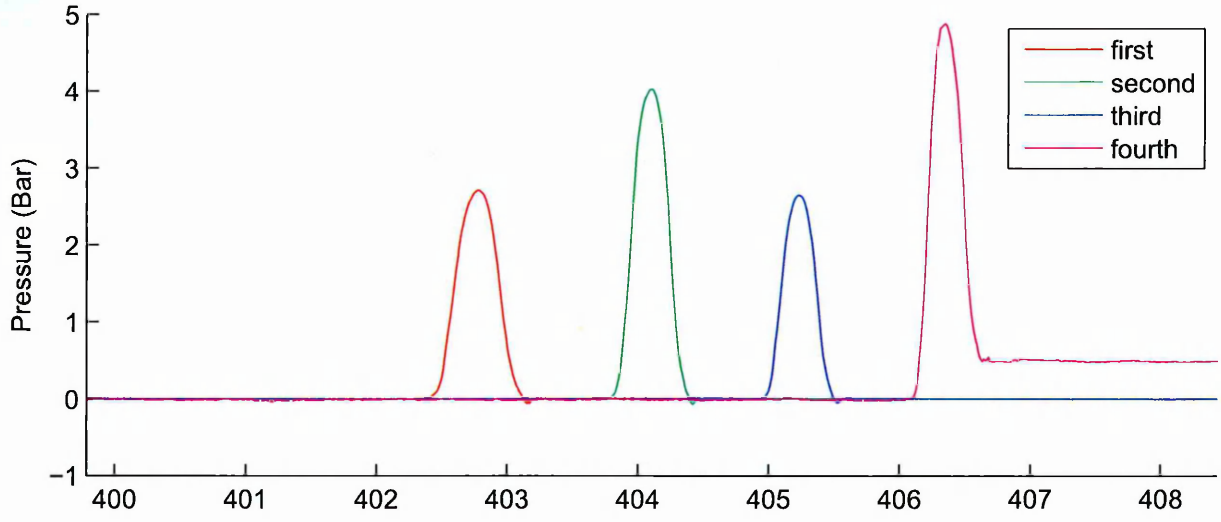

Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2

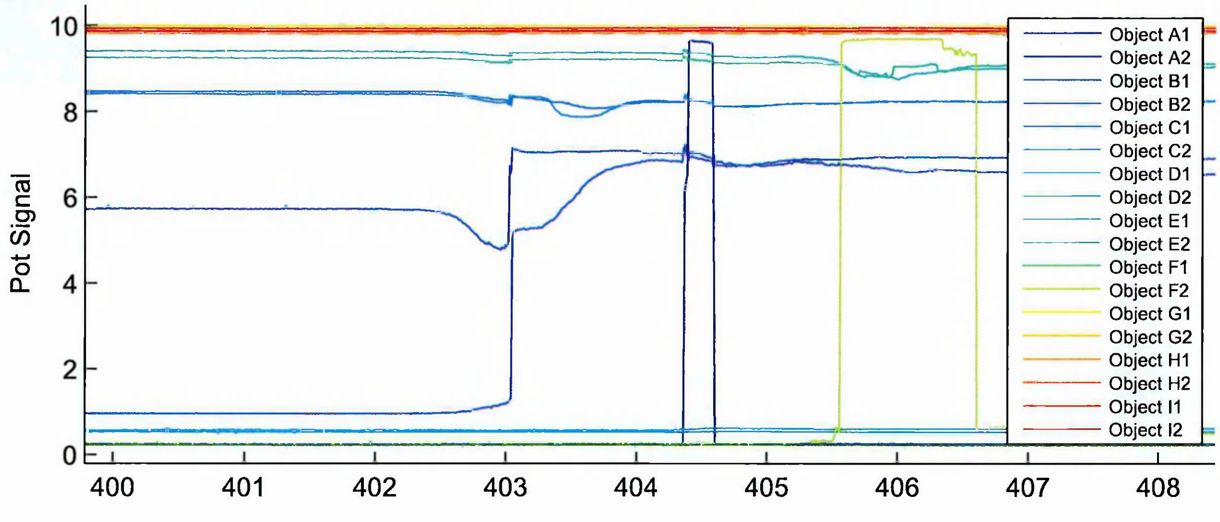

Pots + Bones #1 / Inflation 1.5 bar + Load 3.8 tonnes (1)
Speed (m/s), Distance (m), Load (t)
Time (S)
Speed
Distance
Load

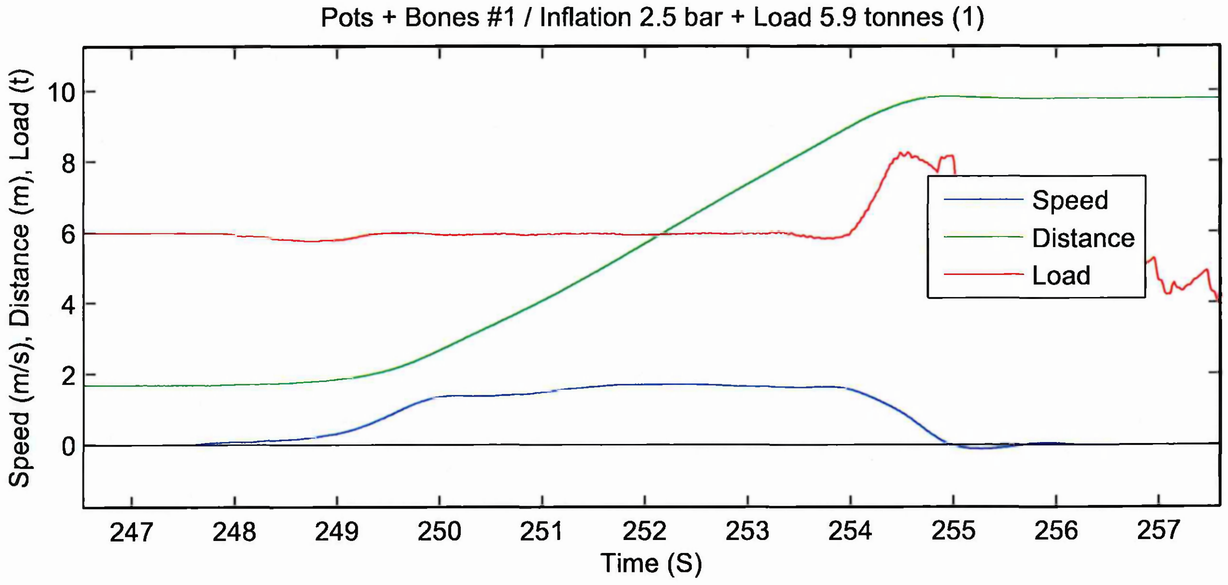

Pressure (Bar)
first
second
third
fourth

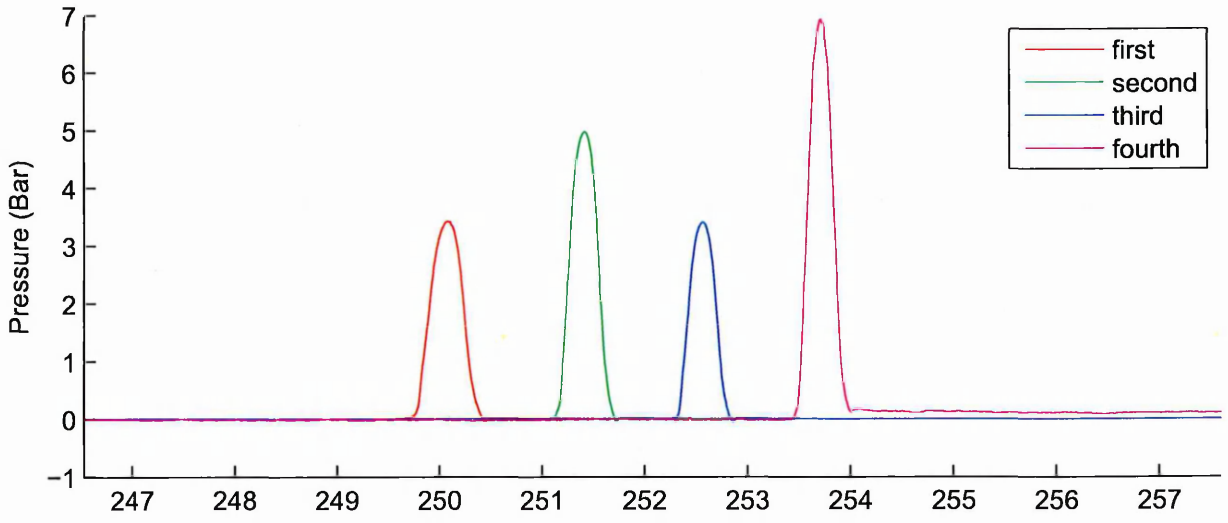

Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2

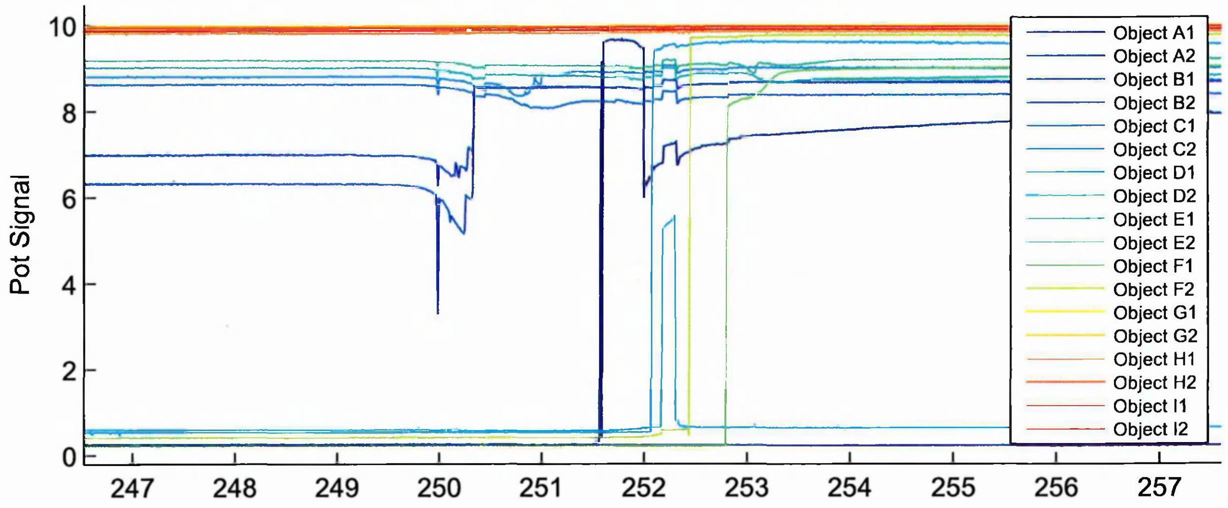

Pots + Bones #1 / Inflation 2.0 bar + Load 4.9 tonnes (1)
Speed (m/s), Distance (m), Load (t)
Time (S)
Speed
Distance
Load
0
2
4
6
8
10
400
401
402
403
404
405
406
407
408

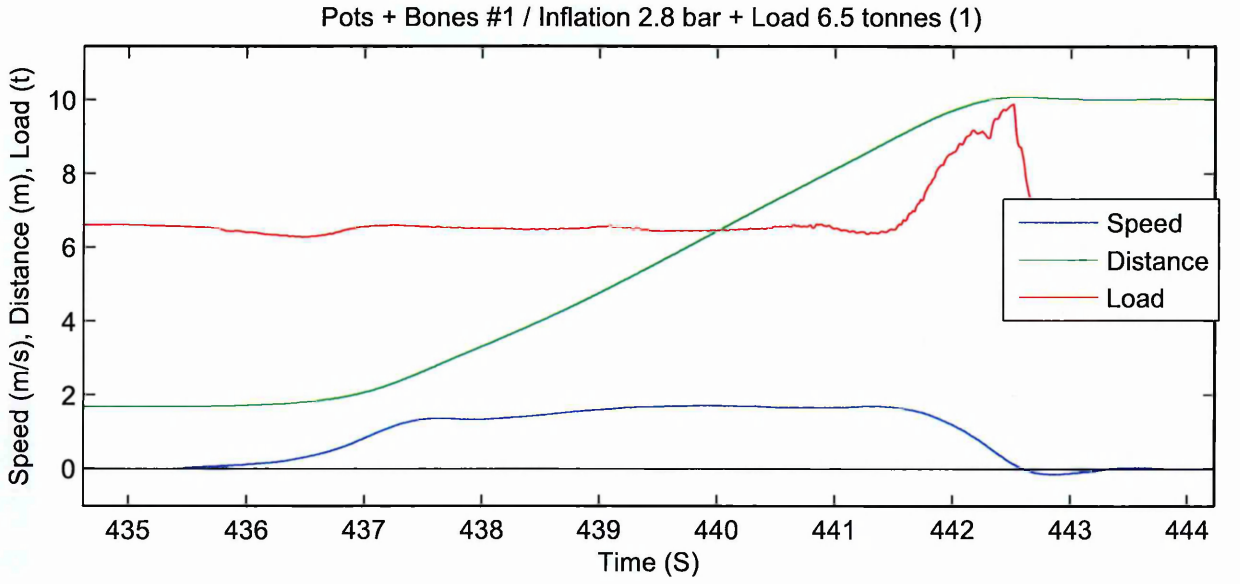

Pressure (Bar)
first
second
third
fourth
−1
0
1
2
3
4
5
400
401
402
403
404
405
406
407
408

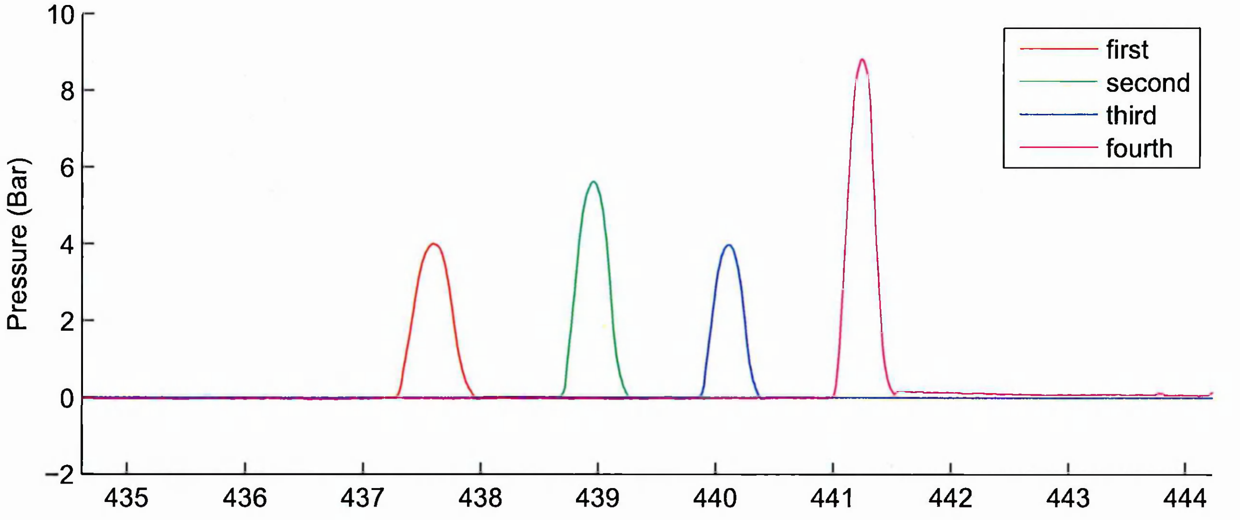

Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
0
2
4
6
8
10
400
401
402
403
404
405
406
407
408

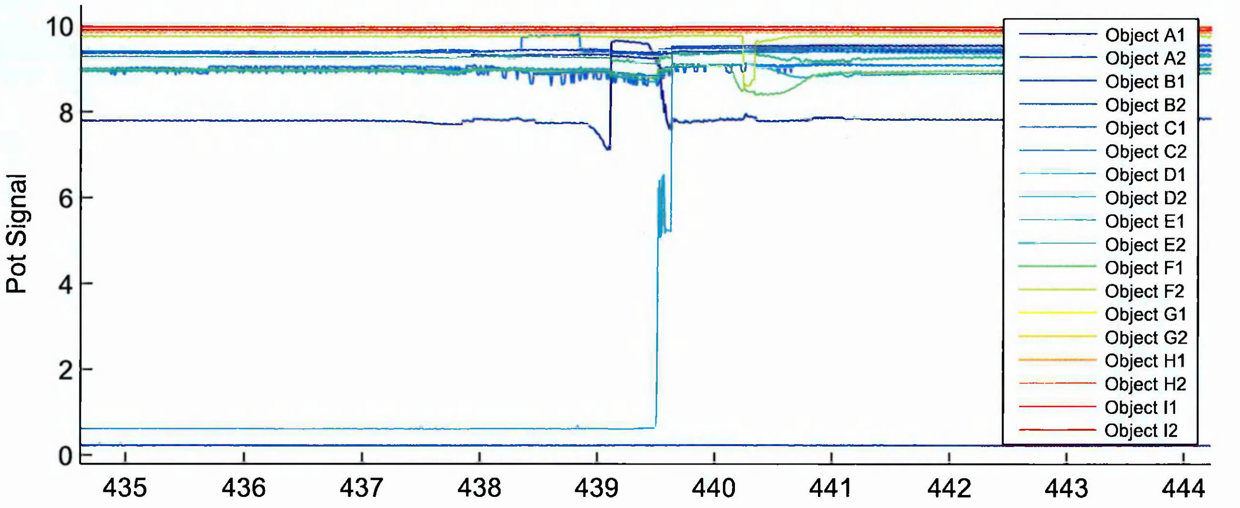

Pots + Bones #1 / Inflation 2.5 bar + Load 5.9 tonnes (1)
Speed (m/s), Distance (m), Load (t)
Time (S)
Speed
Distance
Load
0
2
4
6
8
10
247
248
249
250
251
252
253
254
255
256
257


Pressure (Bar)
first
second
third
fourth
-1
0
1
2
3
4
5
6
7
247
248
249
250
251
252
253
254
255
256
257

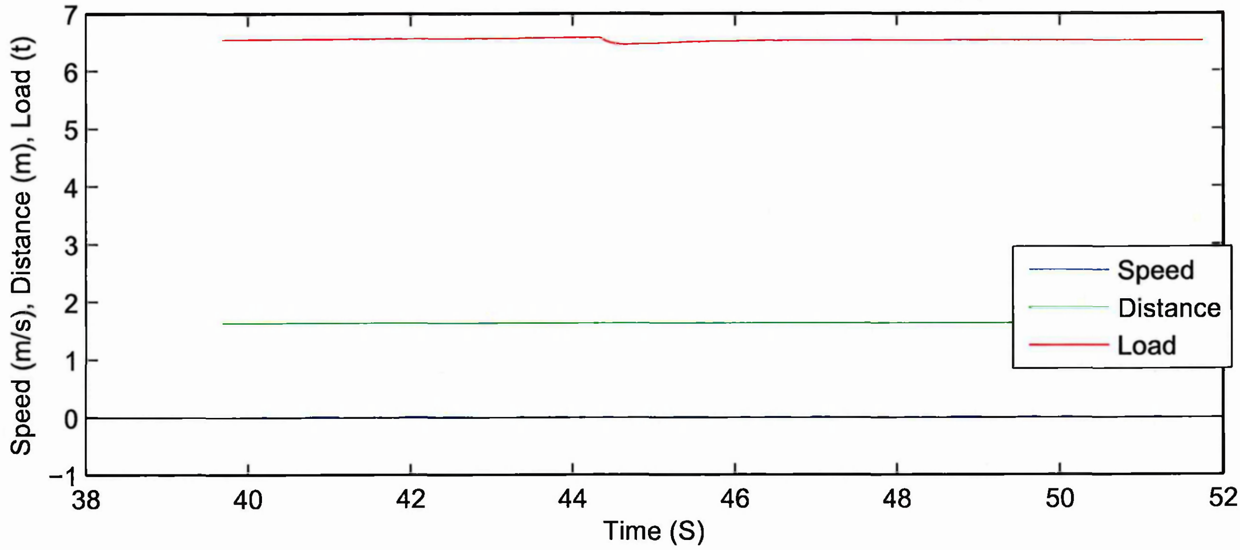

Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
0
2
4
6
8
10
247
248
249
250
251
252
253
254
255
256
257

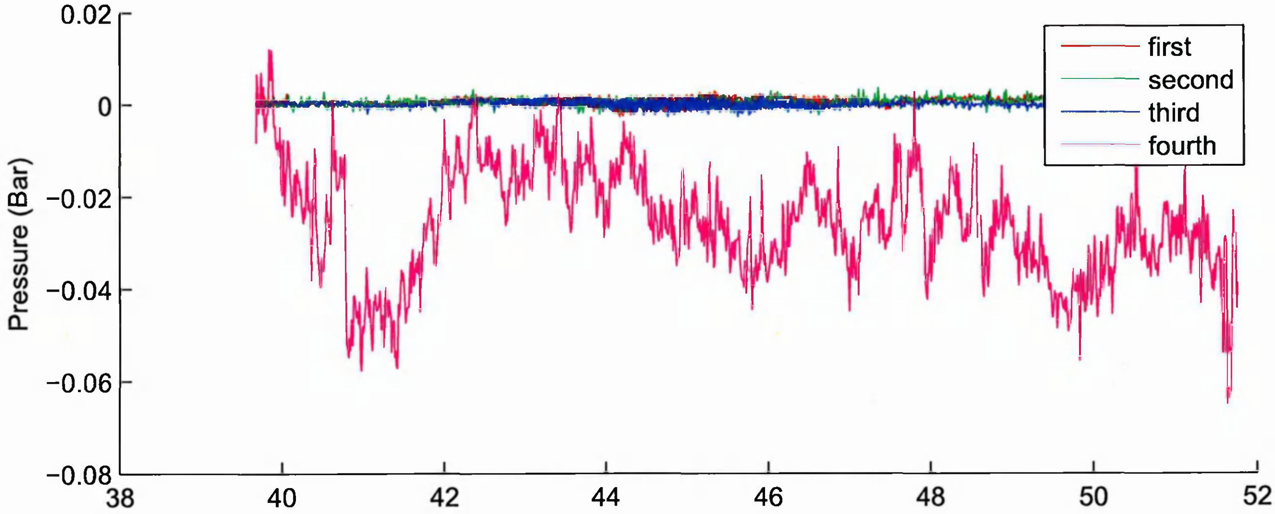

Pots + Bones #1 / Inflation 2.8 bar + Load 6.5 tonnes (1)
Speed (m/s), Distance (m), Load (t)
Time (S)
Speed
Distance
Load

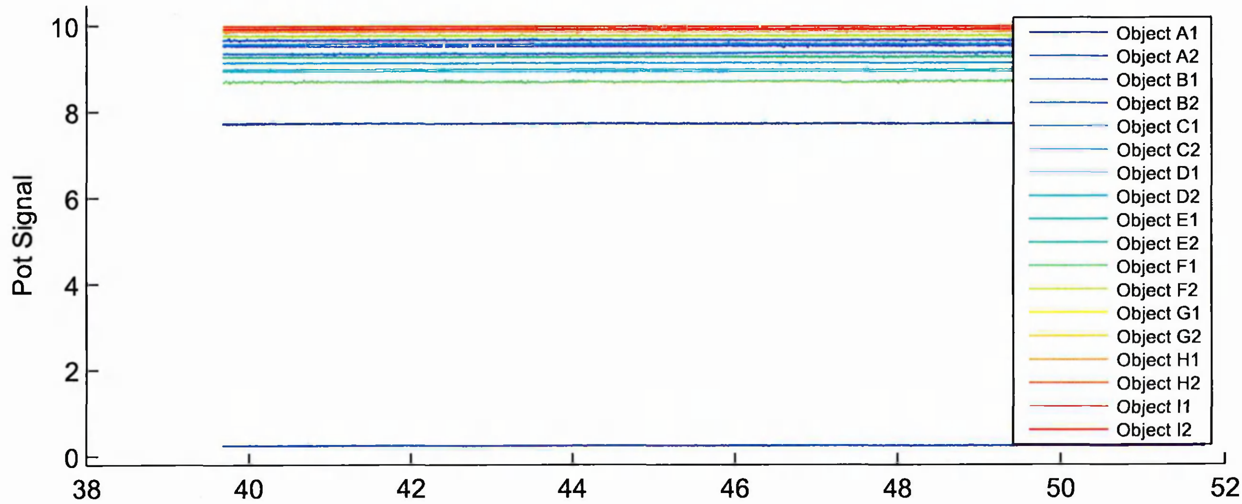

Pressure (Bar)
first
second
third
fourth

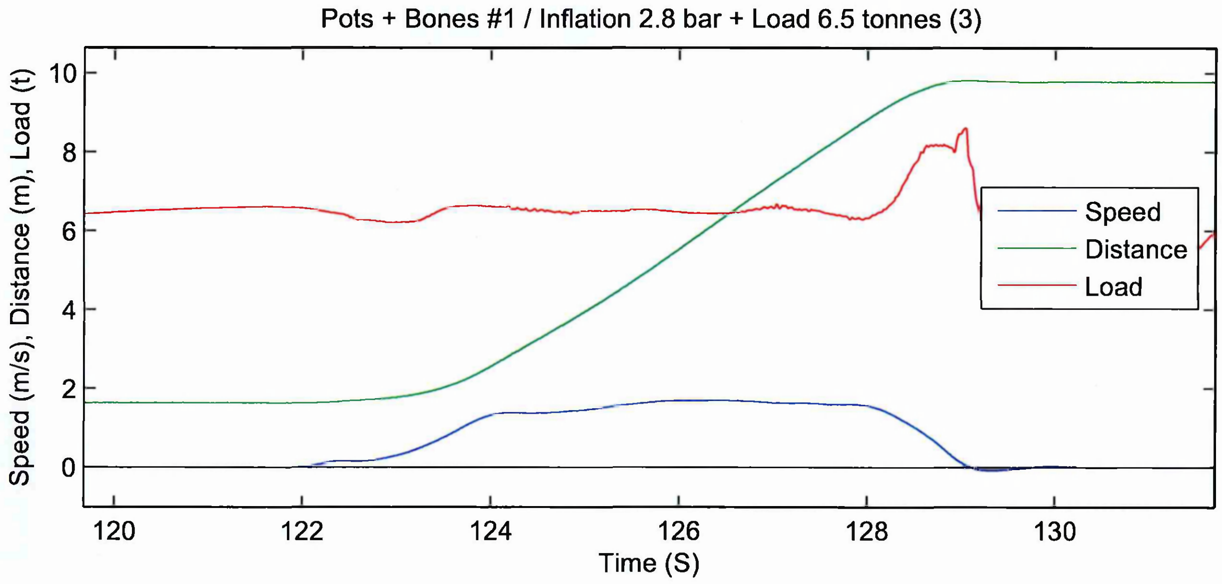

Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2

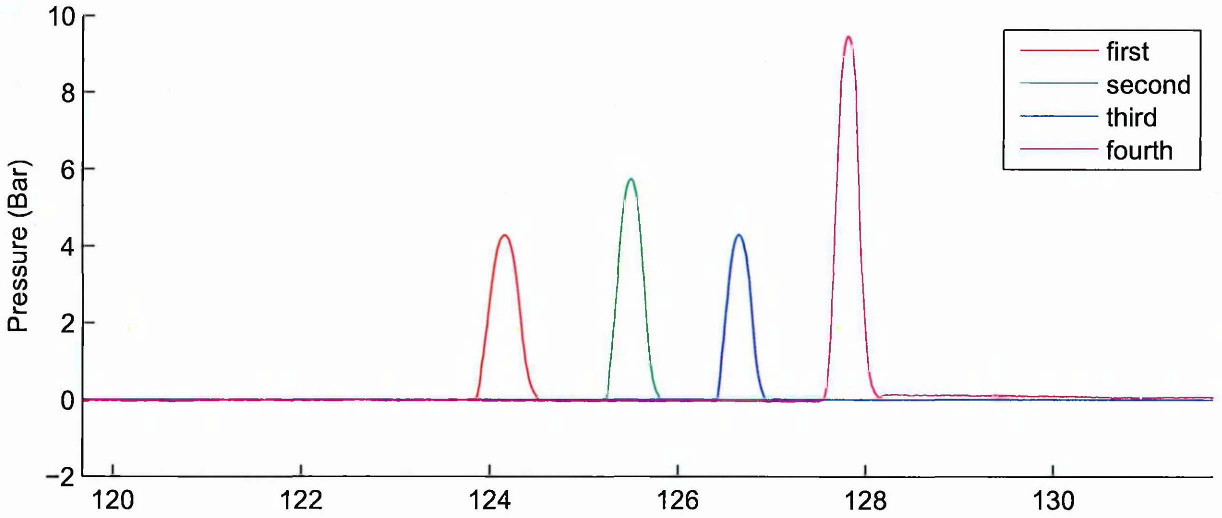
Pots + Bones #1 / Inflation 2.8 bar + Load 6.5 tonnes (2)

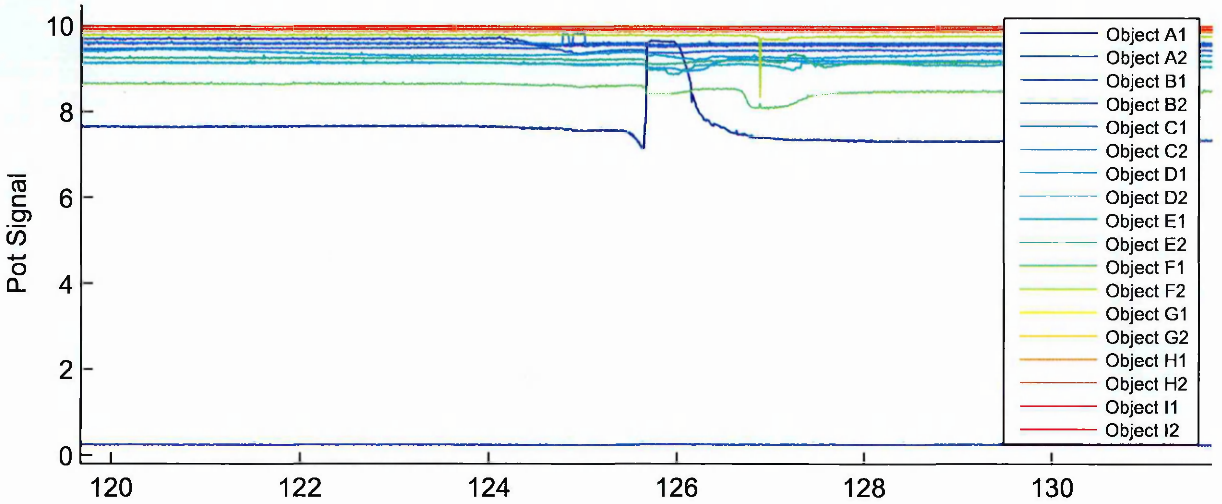


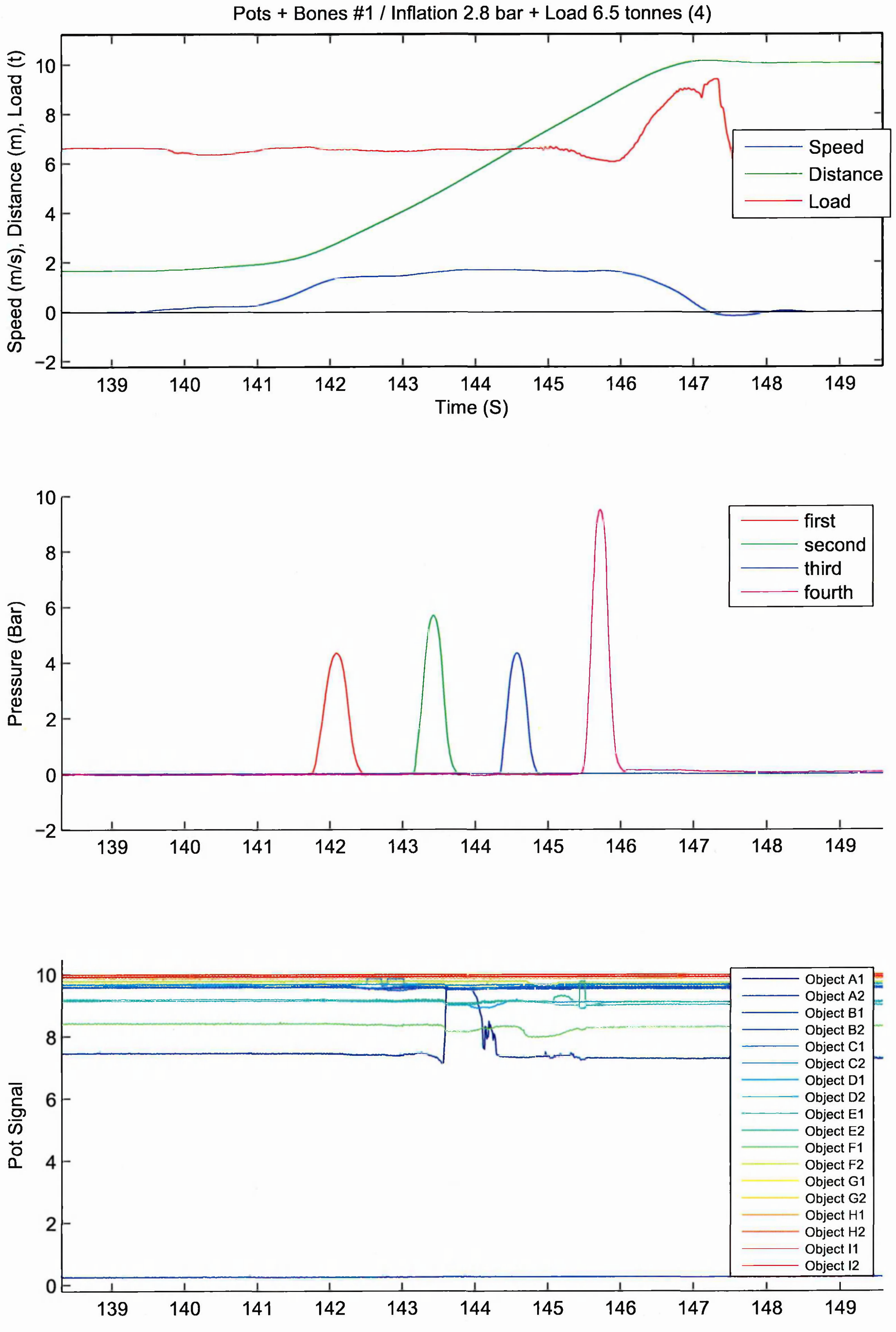


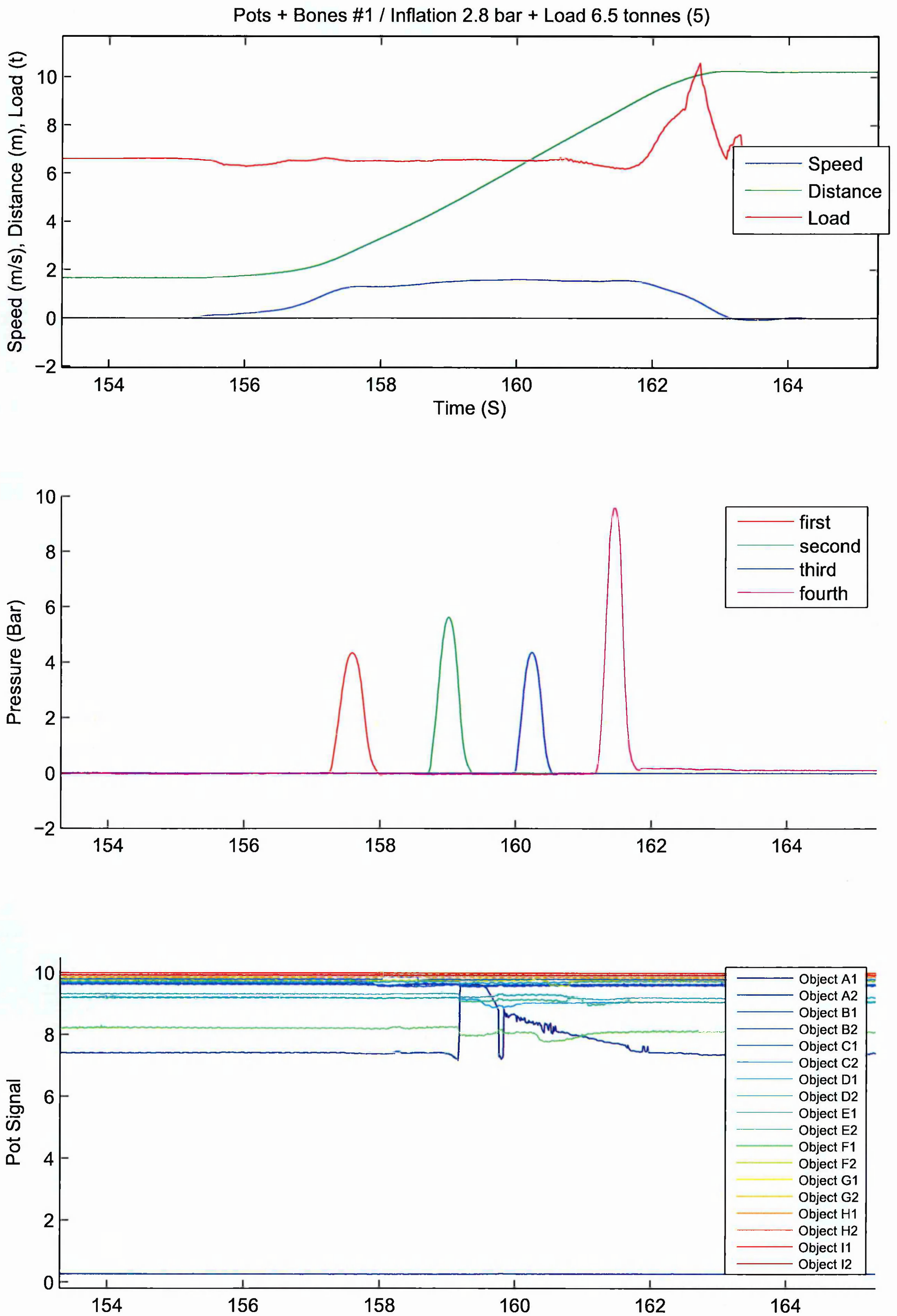


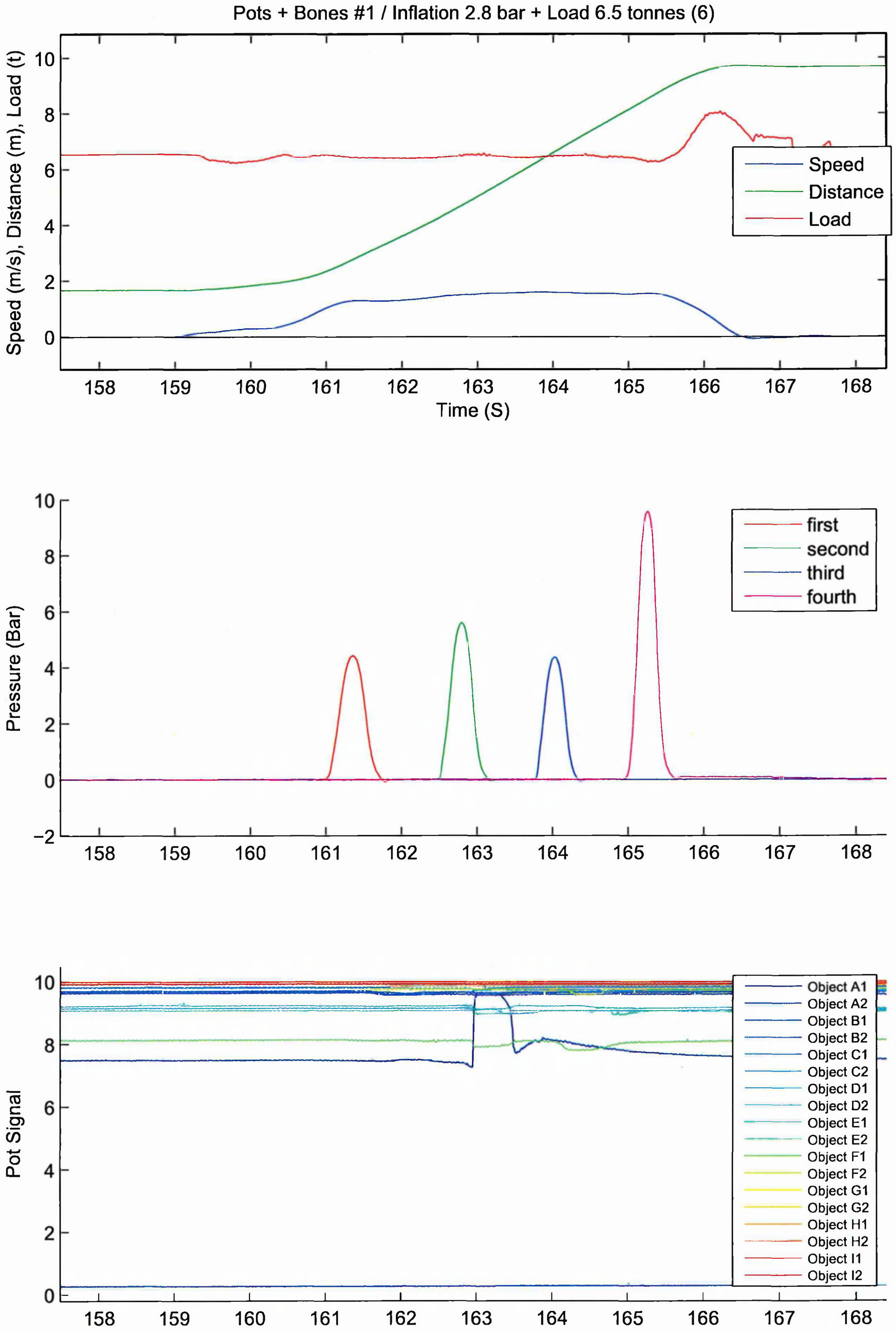

Pots + Bones #1 / Inflation 2.8 bar + Load 6.5 tonnes (3)
Speed (m/s), Distance (m), Load (t)
Time (S)
Speed
Distance
Load
120
122
124
126
128
130
0
2
4
6
8
10


Pressure (Bar)
first
second
third
fourth
120
122
124
126
128
130
-2
0
2
4
6
8
10


Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
120
122
124
126
128
130
0
2
4
6
8
10

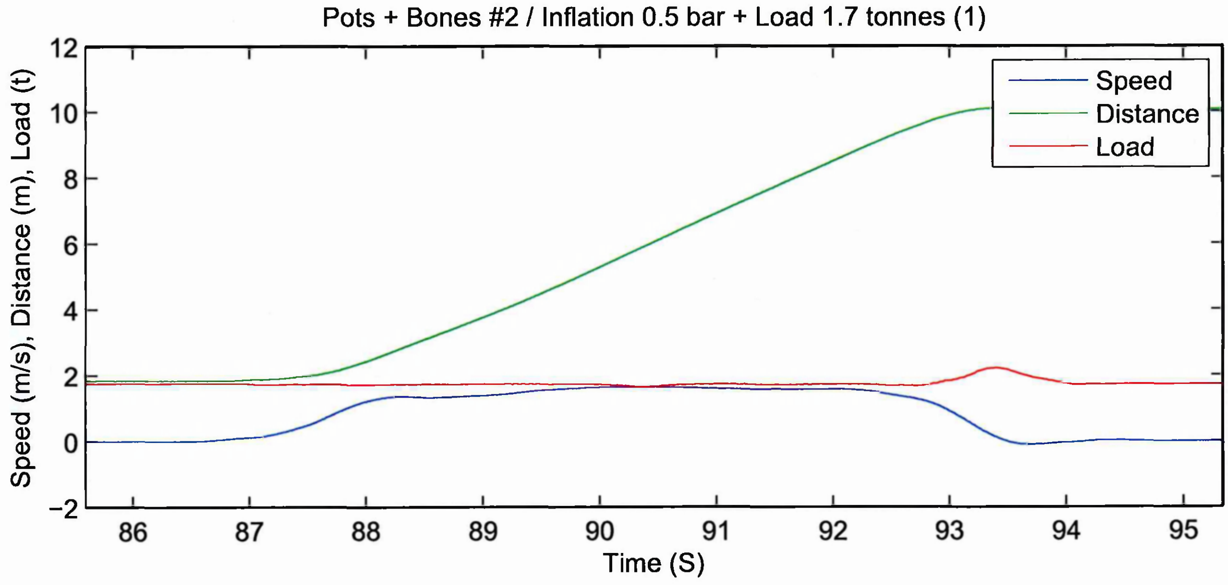

Pots + Bones #1 / Inflation 2.8 bar + Load 6.5 tonnes (4)
Speed (m/s), Distance (m), Load (t)
Speed
Distance
Load
Time (S)
Pressure (Bar)
first
second
third
fourth
Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2

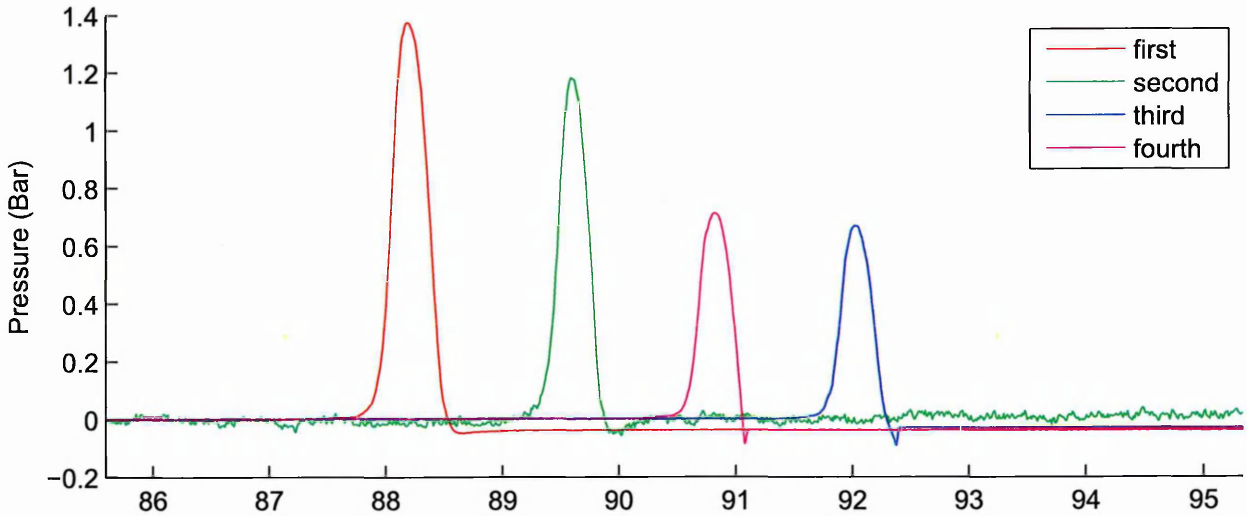

Pots + Bones #1 / Inflation 2.8 bar + Load 6.5 tonnes (5)
Speed (m/s), Distance (m), Load (t)
Speed
Distance
Load
Time (S)
Pressure (Bar)
first
second
third
fourth
Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2

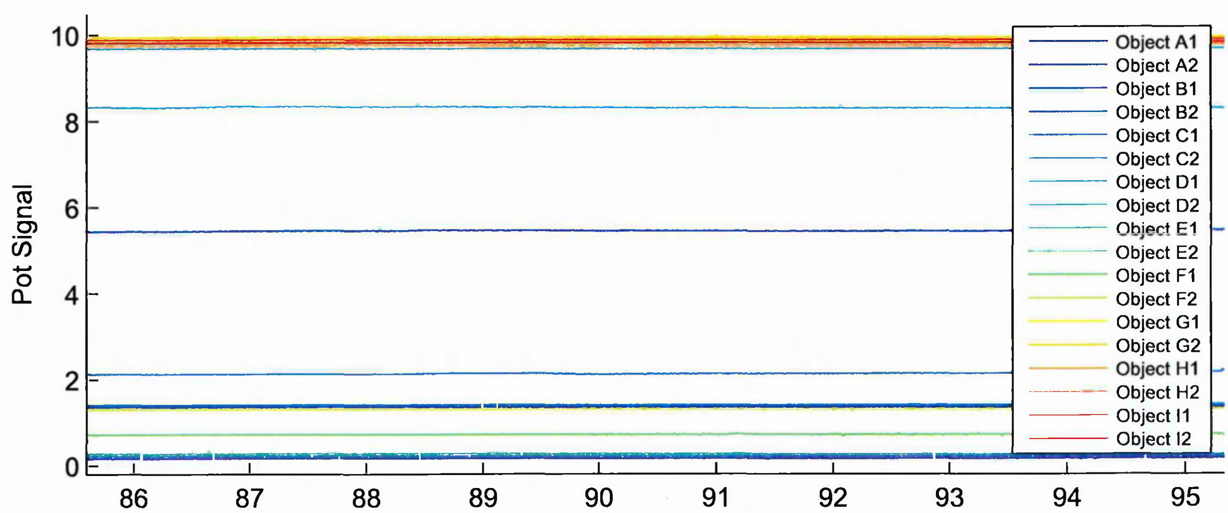


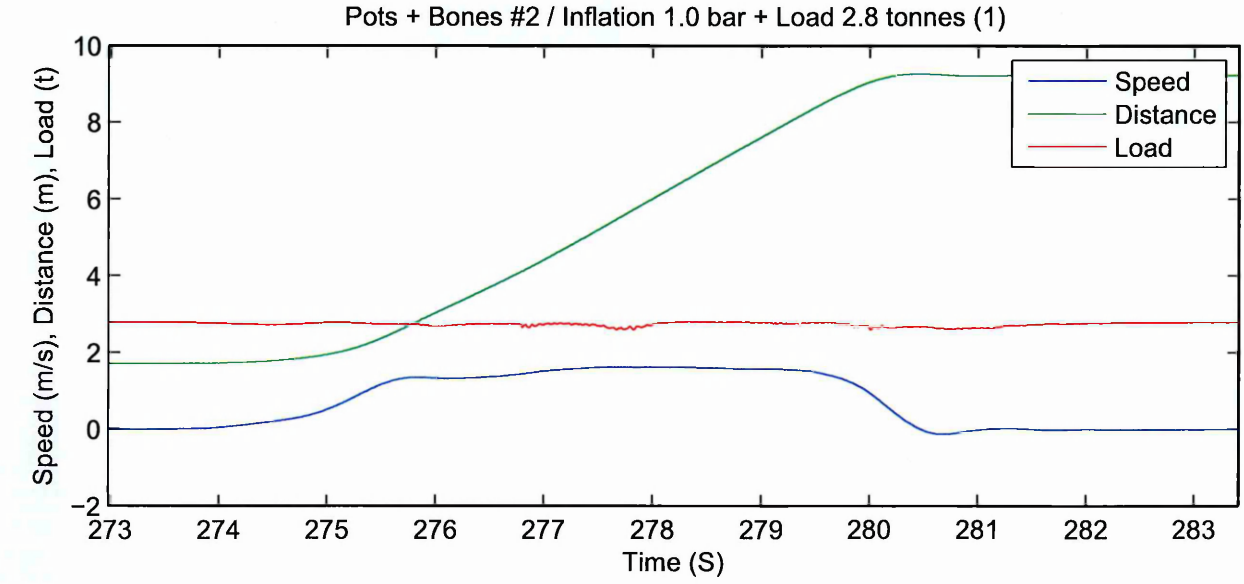
Pots + Bones #1 / Inflation 2.8 bar + Load 6.5 tonnes (6)
Speed (m/s), Distance (m), Load (t)
Time (S)
Speed
Distance
Load
Pressure (Bar)
first
second
third
fourth
Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2

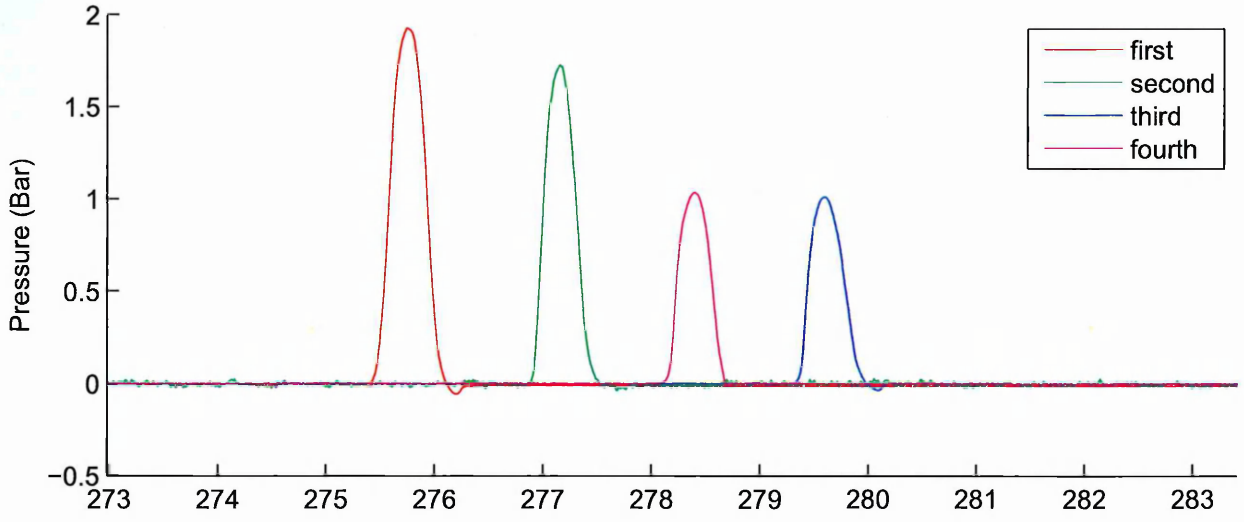
R2	R2
Object A1	roman thrown rim
Object A2	roman thrown body
Object B1	bone perpendicular bottom
Object B2	bone perpendicular top
Object C1	sand + flint tempered rim
Object C2	sand + flint tempered body
Object D1	flint beaker body
Object D2	flint beaker rim
Object E1	bone parallel top
Object E2	bone parallel bottom
Object F1	shell tempered rim
Object F2	shell tempered body
Object G1	X
Object G2	X
Object H1	X
Object H2	X
Object I1	X
Object I2	X

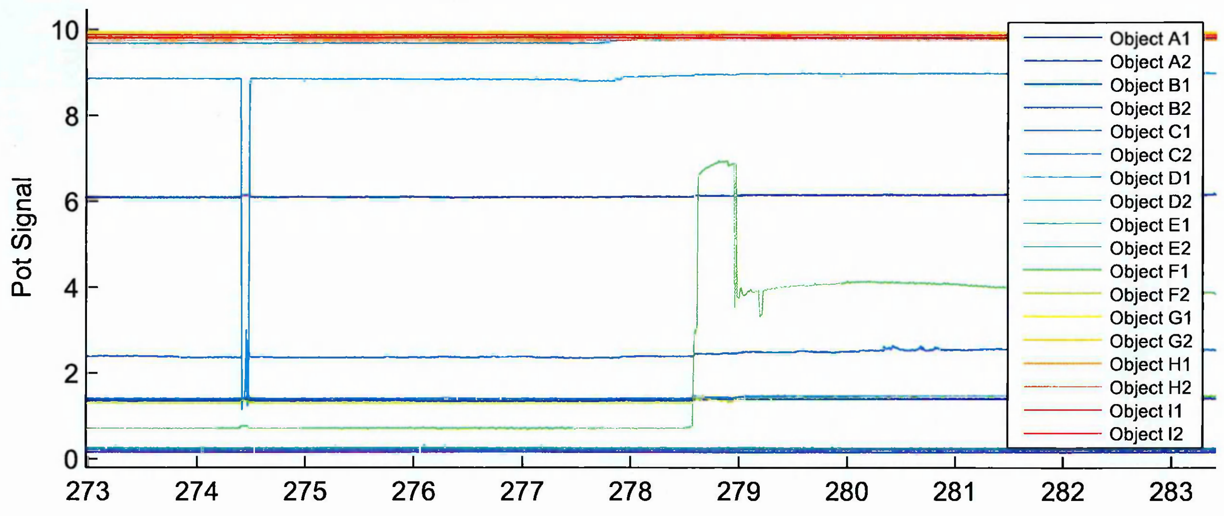

Pots + Bones #2 / Inflation 0.5 bar + Load 1.7 tonnes (1)
Speed
Distance
Load
Speed (m/s), Distance (m), Load (t)
Time (S)
12
10
8
6
4
2
0
−2
86
87
88
89
90
91
92
93
94
95

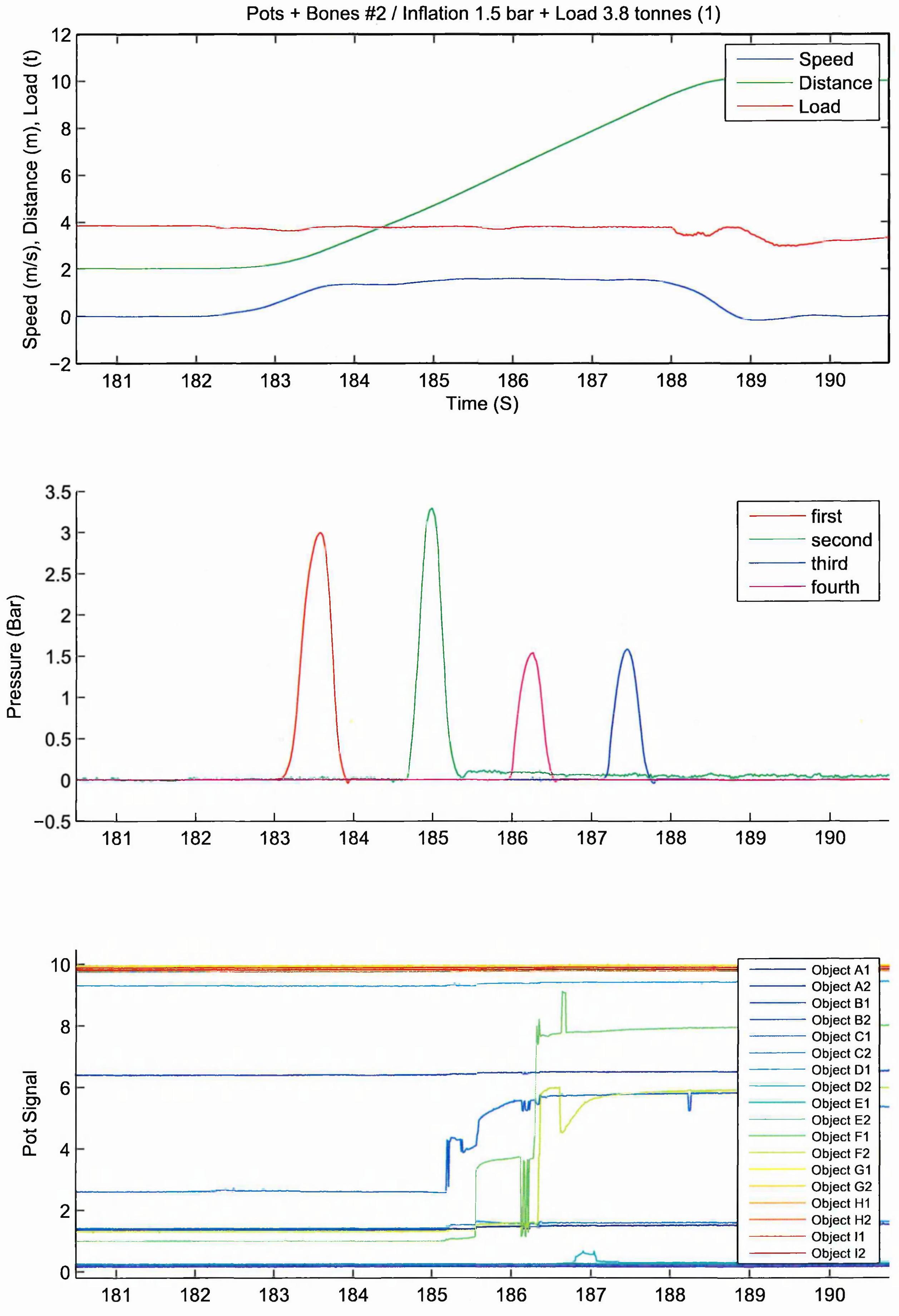

first
second
third
fourth
Pressure (Bar)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
86
87
88
89
90
91
92
93
94
95


Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
Pot Signal
10
8
6
4
2
0
86
87
88
89
90
91
92
93
94
95

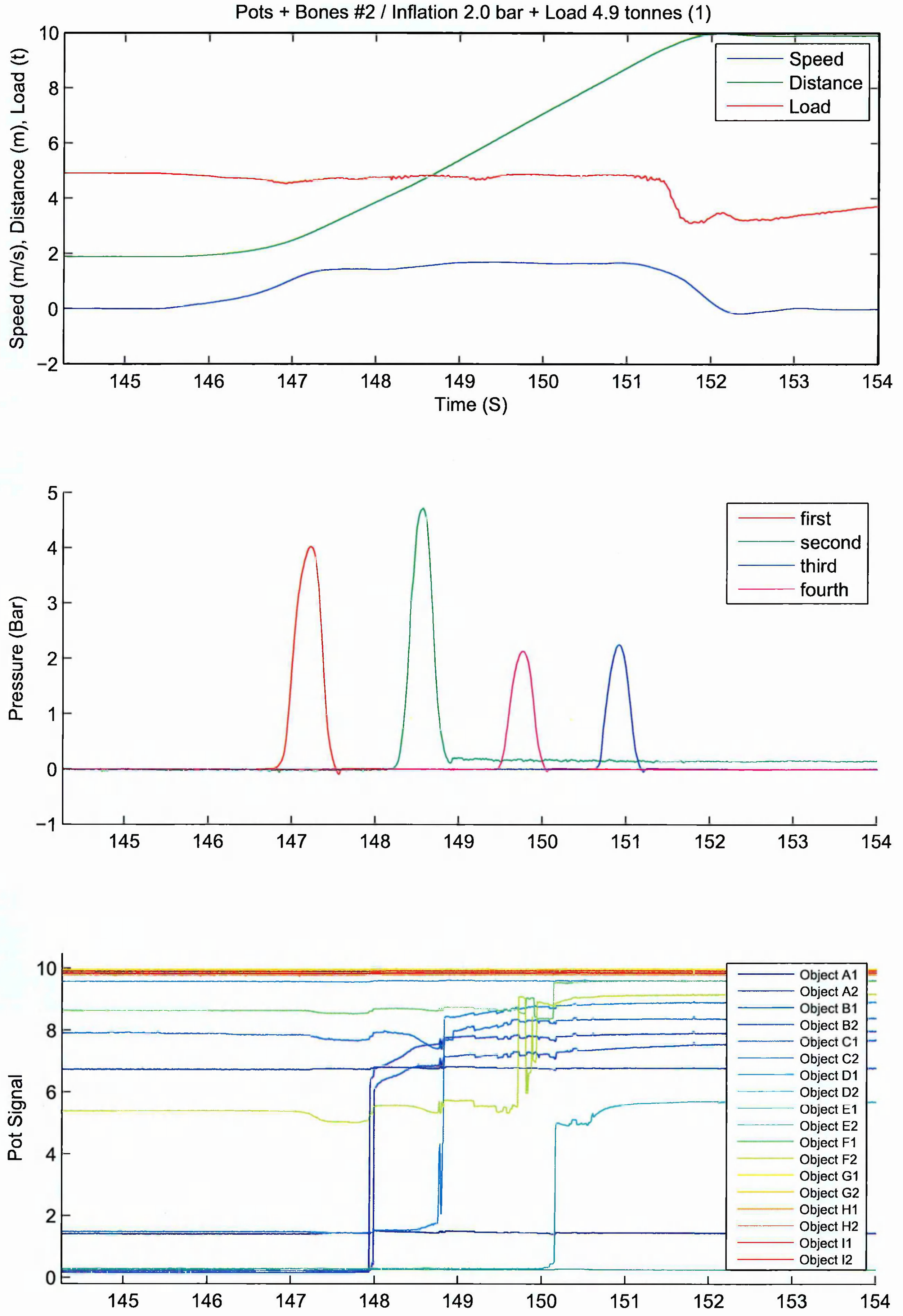

Pots + Bones #2 / Inflation 1.0 bar + Load 2.8 tonnes (1)
Speed
Distance
Load
Speed (m/s), Distance (m), Load (t)
10
8
6
4
2
0
−2
273
274
275
276
277
278
279
280
281
282
283
Time (S)


first
second
third
fourth
Pressure (Bar)
2
1.5
1
0.5
0
−0.5
273
274
275
276
277
278
279
280
281
282
283

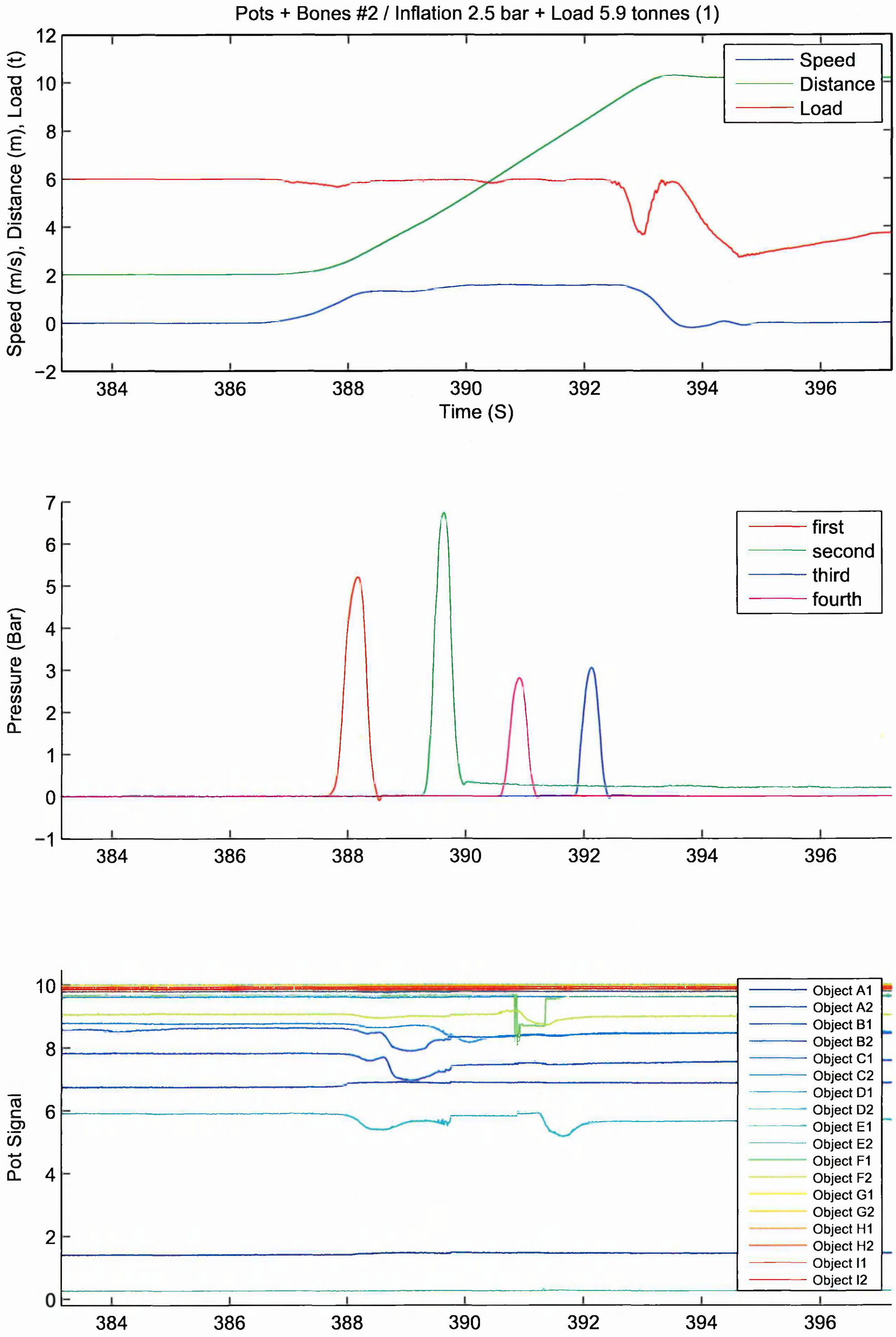

Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
Pot Signal
10
8
6
4
2
0
273
274
275
276
277
278
279
280
281
282
283



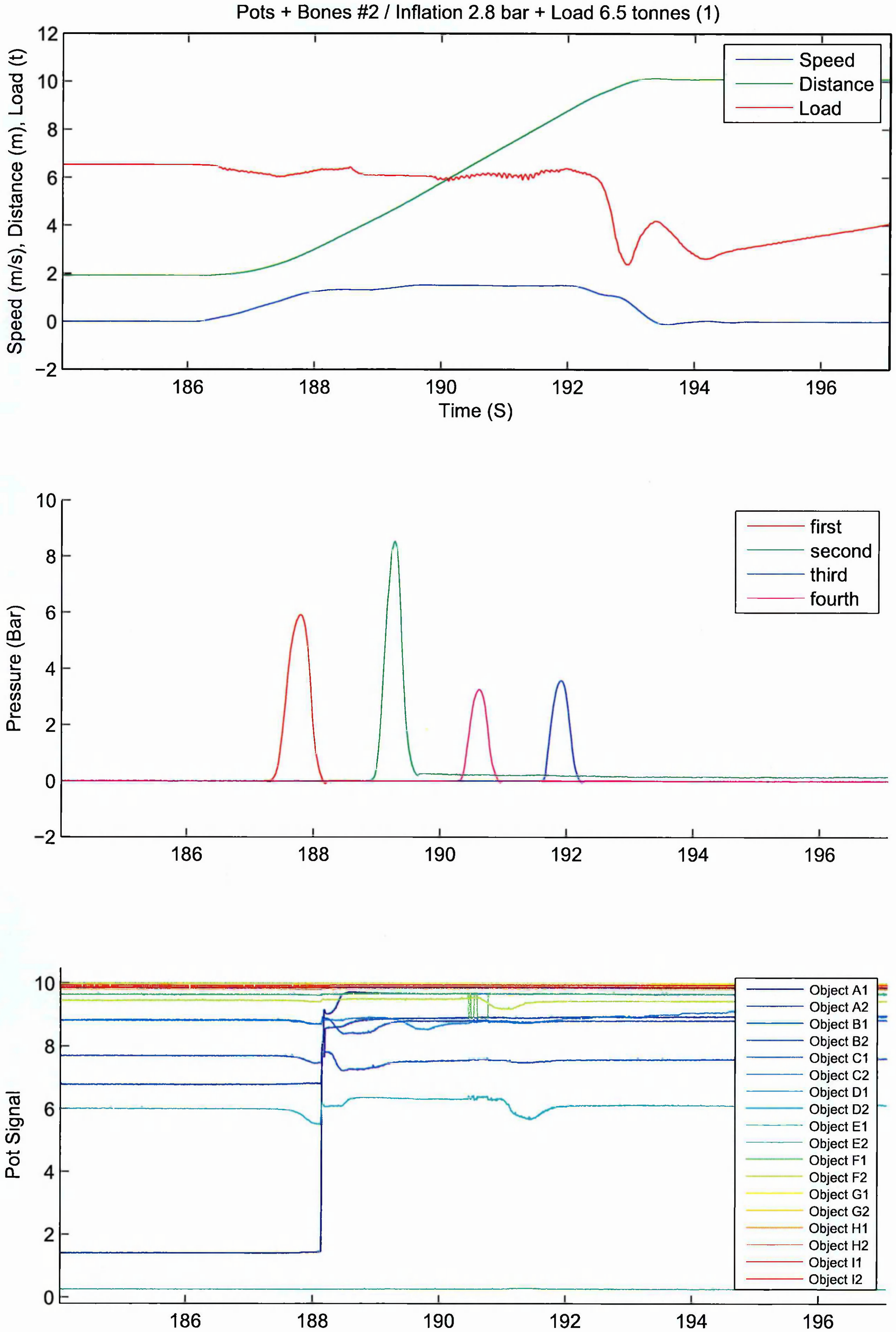
Pots + Bones #2 / Inflation 1.5 bar + Load 3.8 tonnes (1)
Speed (m/s), Distance (m), Load (t)
Speed
Distance
Load
Time (S)
Pressure (Bar)
first
second
third
fourth
Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2

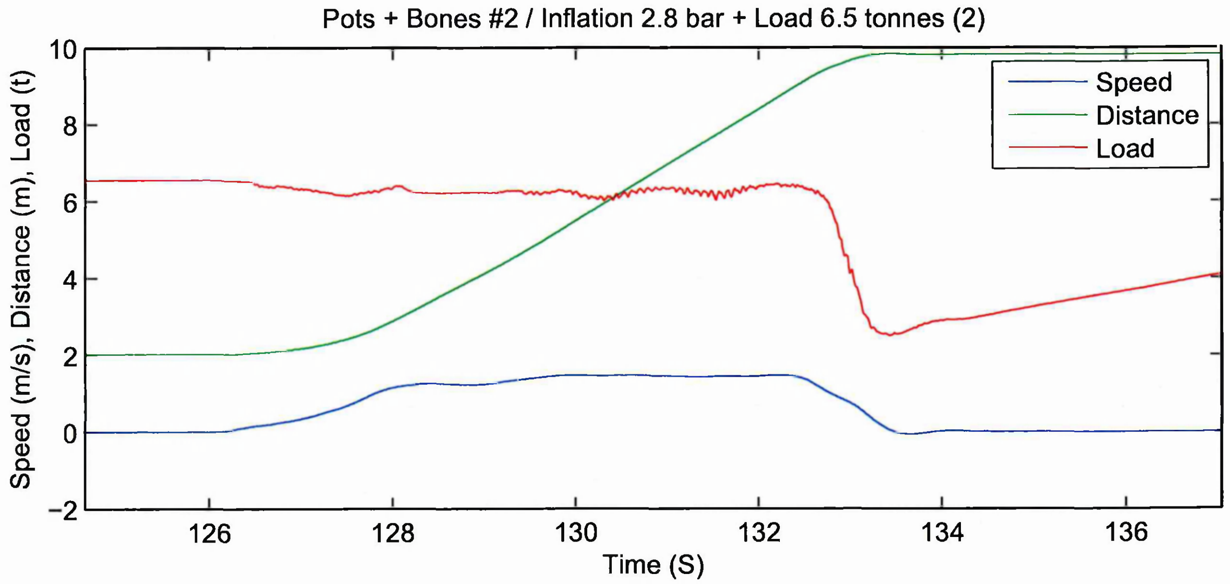


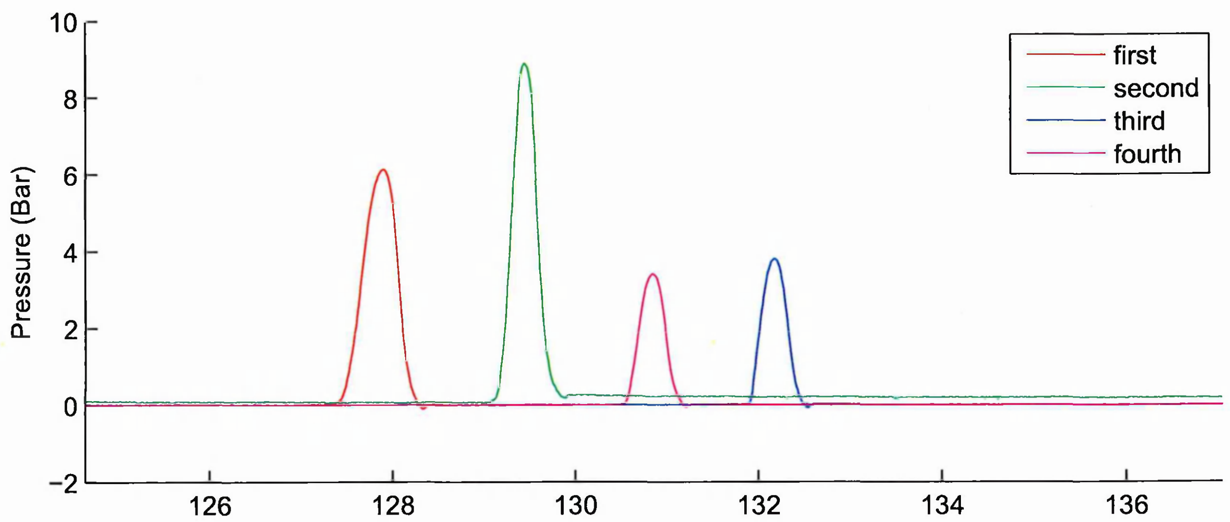
Pots + Bones #2 / Inflation 2.0 bar + Load 4.9 tonnes (1)
Speed
Distance
Load
Speed (m/s), Distance (m), Load (t)
Time (S)
first
second
third
fourth
Pressure (Bar)
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
Pot Signal

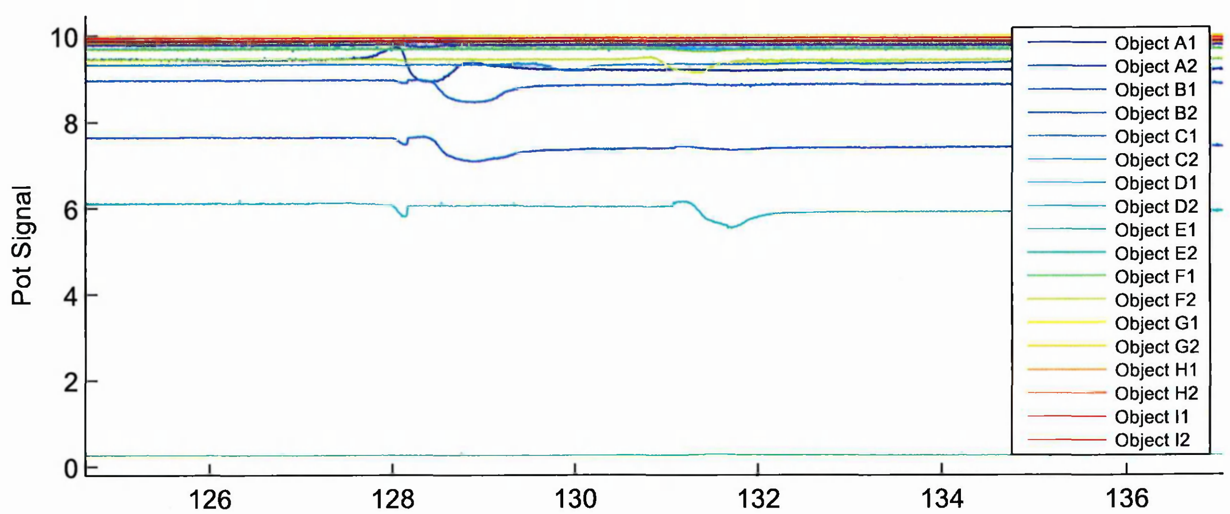


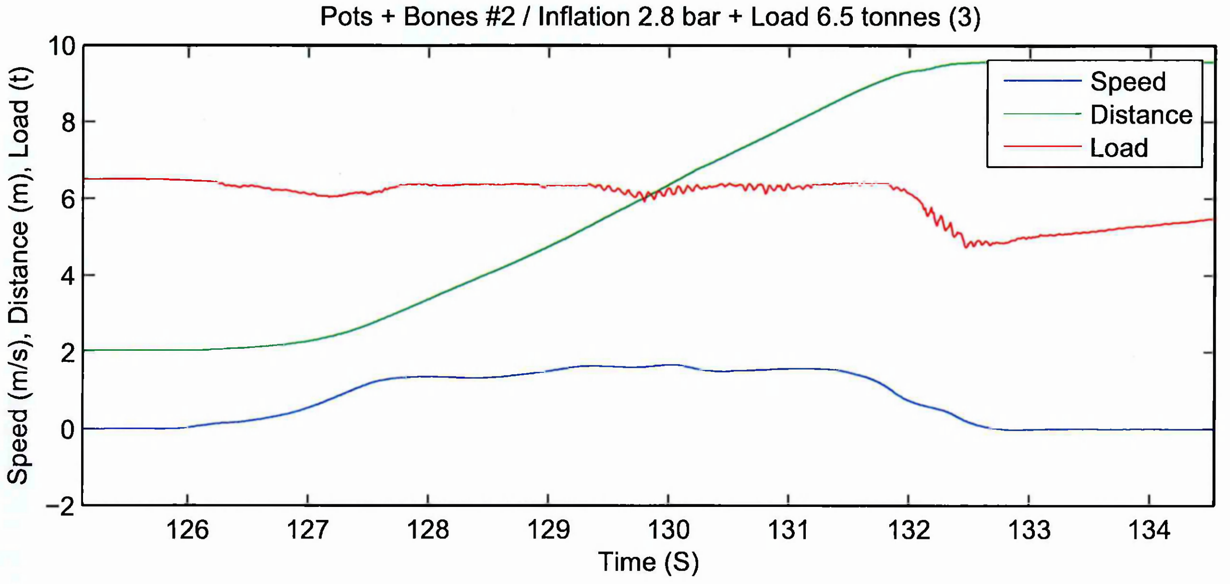
Pots + Bones #2 / Inflation 2.5 bar + Load 5.9 tonnes (1)
Speed
Distance
Load
Speed (m/s), Distance (m), Load (t)
Time (S)
first
second
third
fourth
Pressure (Bar)
Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2

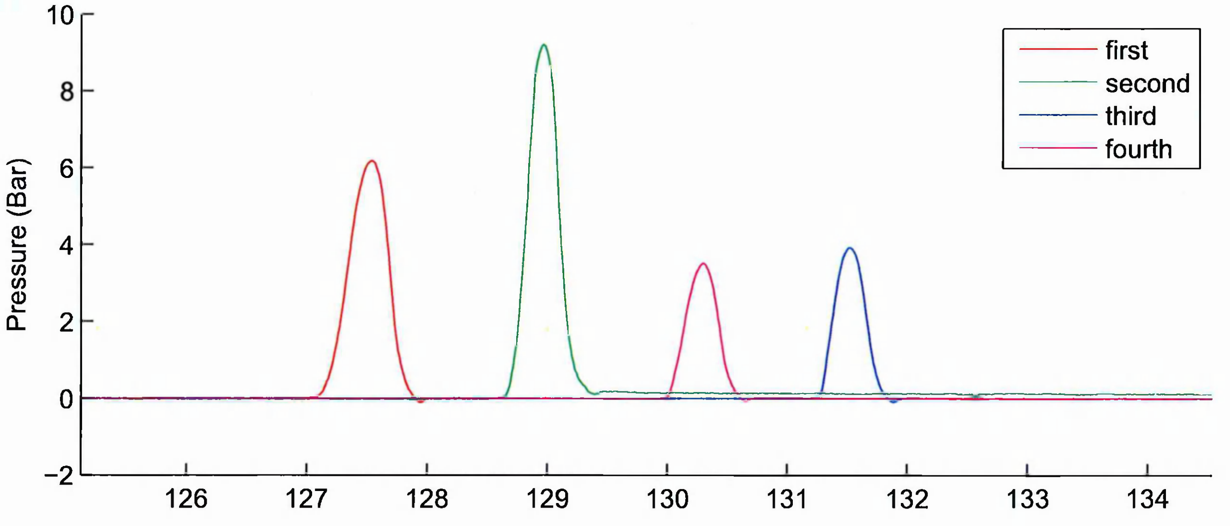

Pots + Bones #2 / Inflation 2.8 bar + Load 6.5 tonnes (1)
Speed
Distance
Load
Speed (m/s), Distance (m), Load (t)
Time (S)
first
second
third
fourth
Pressure (Bar)
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
Pot Signal

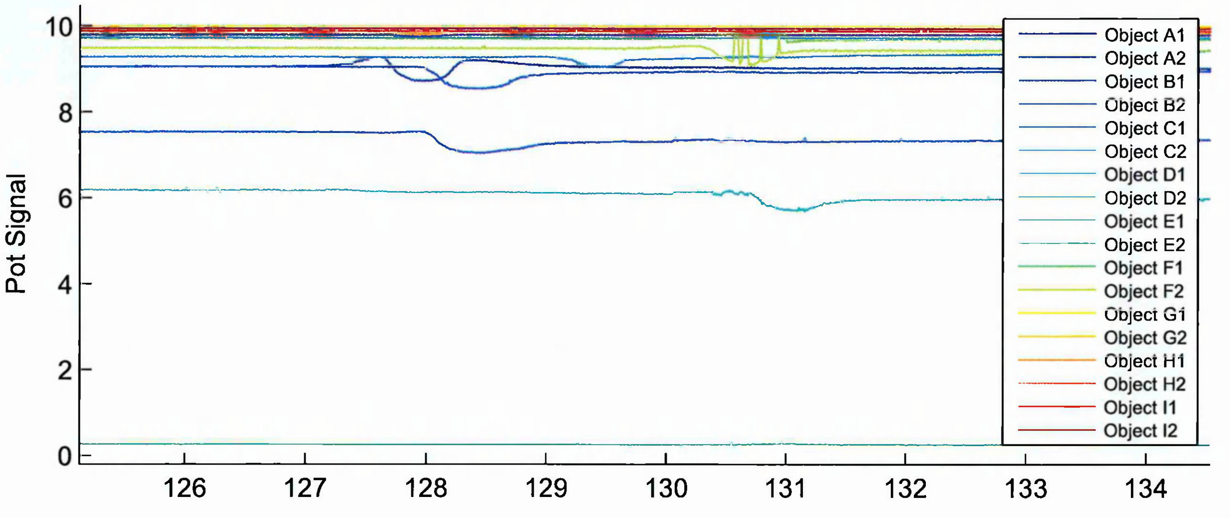

Pots + Bones #2 / Inflation 2.8 bar + Load 6.5 tonnes (2)
Speed (m/s), Distance (m), Load (t)
Time (S)
Speed
Distance
Load
10
8
6
4
2
0
-2
126
128
130
132
134
136

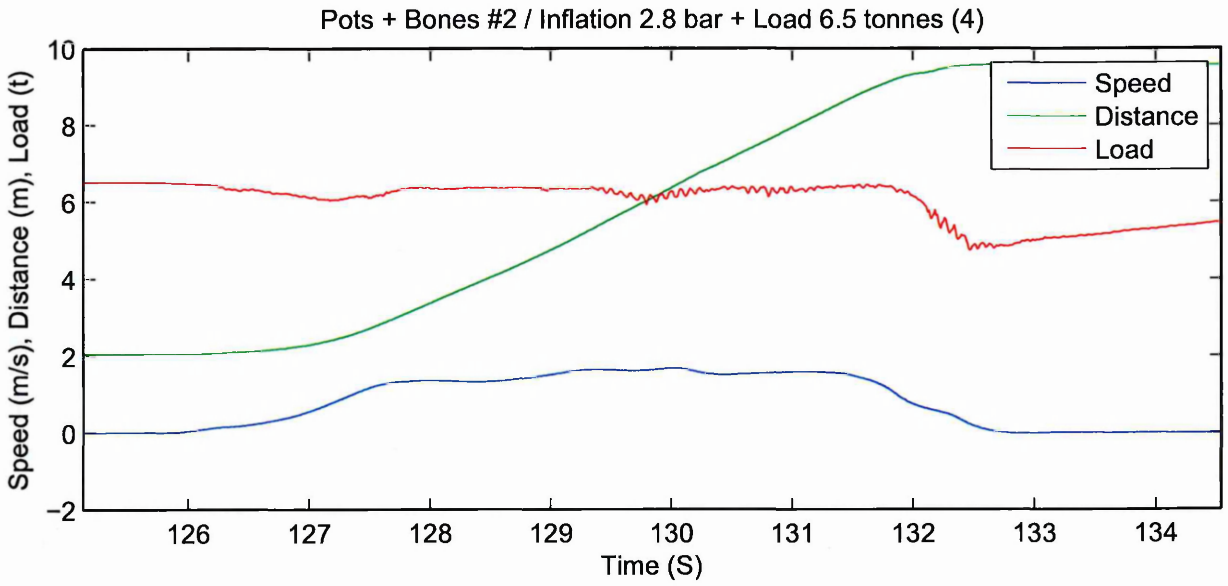

Pressure (Bar)
first
second
third
fourth
10
8
6
4
2
0
-2
126
128
130
132
134
136

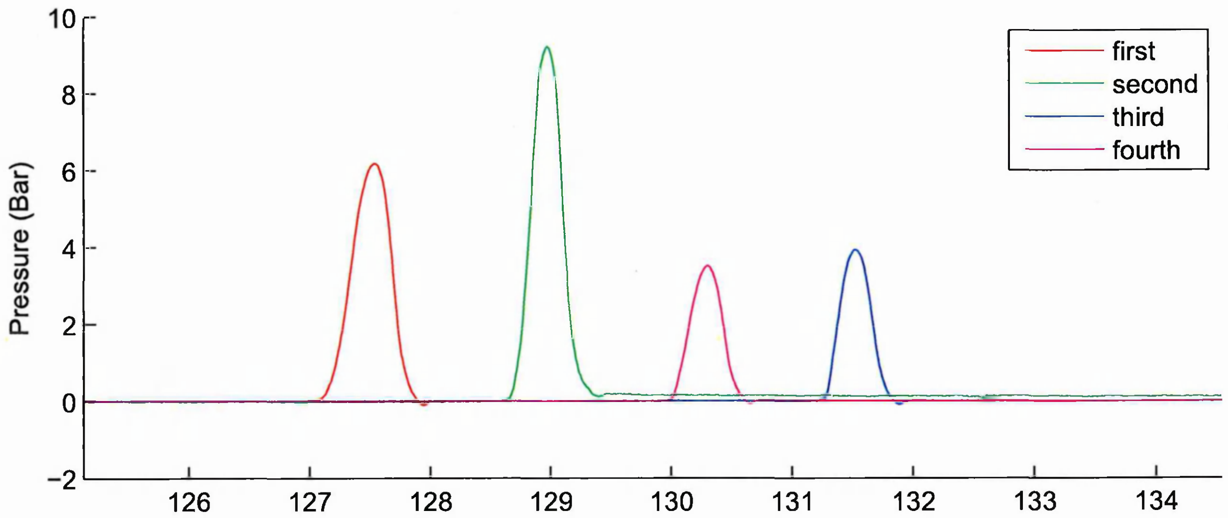

Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
10
8
6
4
2
0
126
128
130
132
134
136

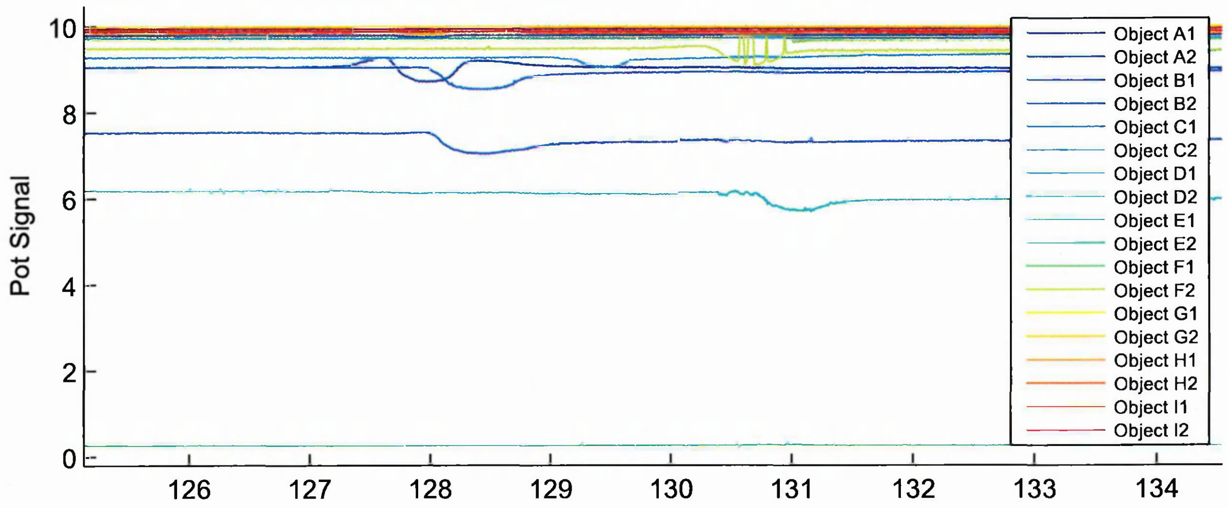

Pots + Bones #2 / Inflation 2.8 bar + Load 6.5 tonnes (3)
Speed (m/s), Distance (m), Load (t)
Speed
Distance
Load
Time (S)


Pressure (Bar)
first
second
third
fourth

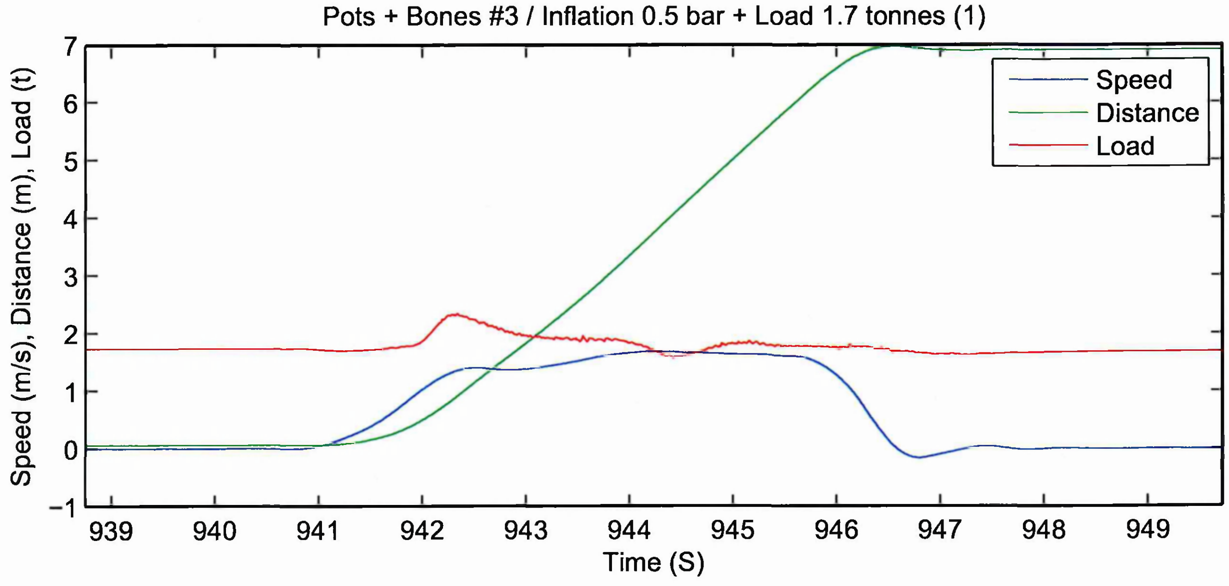

Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2

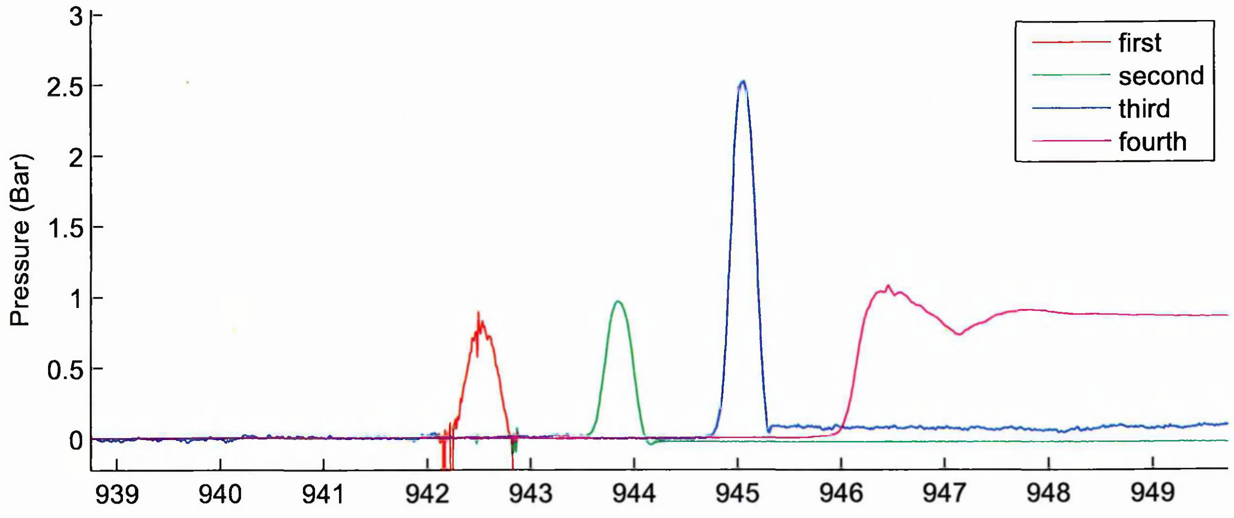

Pots + Bones #2 / Inflation 2.8 bar + Load 6.5 tonnes (4)
Speed (m/s), Distance (m), Load (t)
10
8
6
4
2
0
−2
126
127
128
129
130
131
132
133
134
Time (S)
Speed
Distance
Load

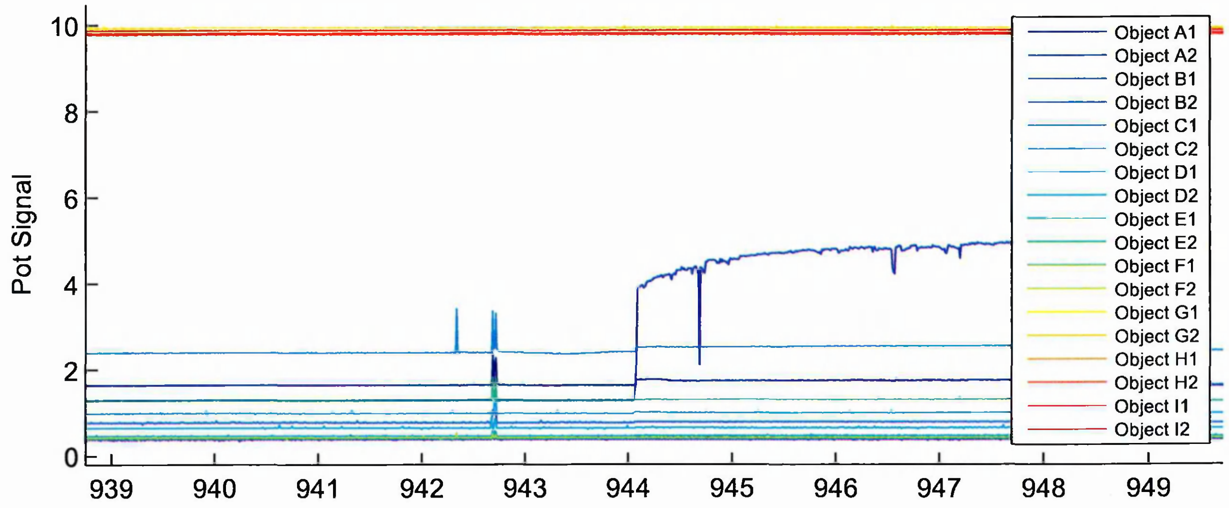

Pressure (Bar)
10
8
6
4
2
0
−2
126
127
128
129
130
131
132
133
134
first
second
third
fourth

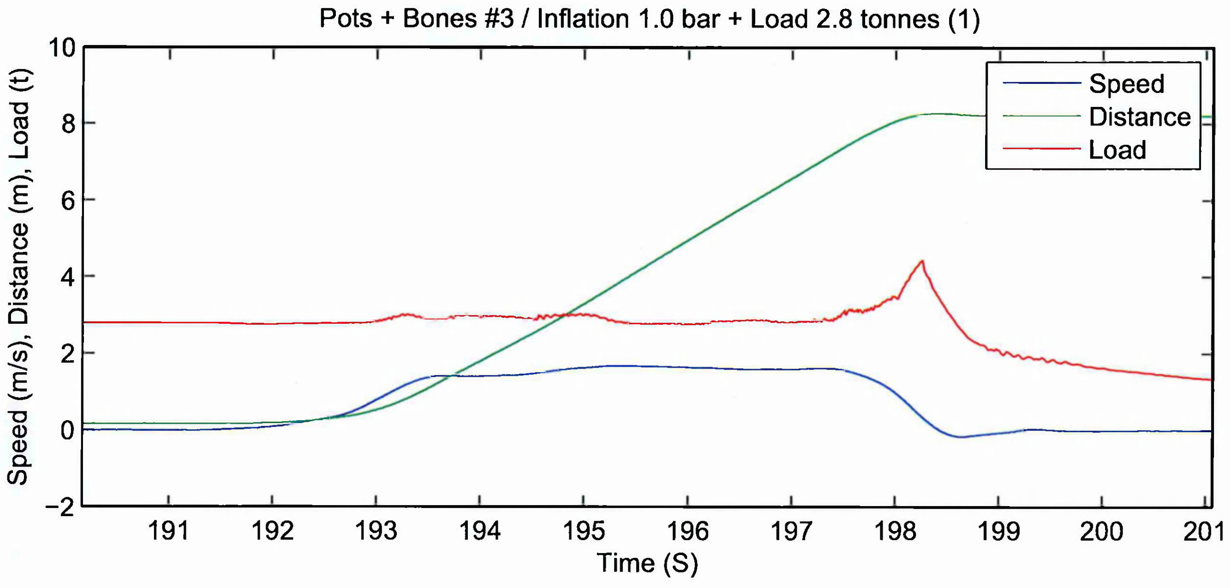

Pot Signal
10
8
6
4
2
0
126
127
128
129
130
131
132
133
134
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2

R3	R3
Object A1	shell tempered body
Object A2	shell tempered rim
Object B1	bone parallel top
Object B2	bone parallel bottom
Object C1	flint beaker rim
Object C2	flint beaker body
Object D1	sand + flint tempered rim
Object D2	sand + flint tempered body
Object E1	roman thrown rim
Object E2	roman thrown body
Object F1	bone perpendicular bottom
Object F2	bone perpendicular top
Object G1	X
Object G2	X
Object H1	X
Object H2	X
Object I1	X
Object I2	X

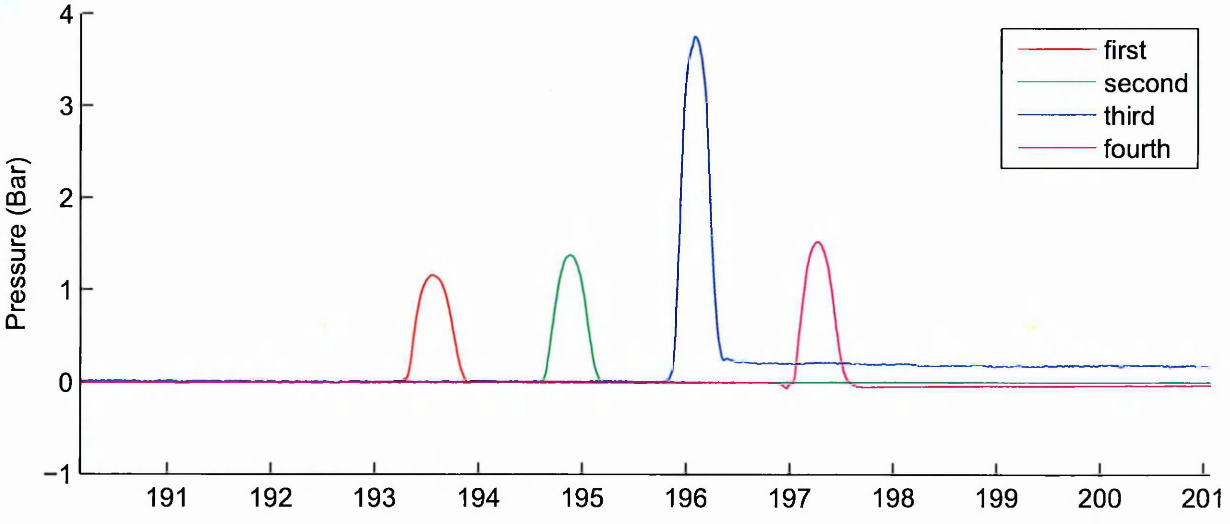

Pots + Bones #3 / Inflation 0.5 bar + Load 1.7 tonnes (1)
Speed (m/s), Distance (m), Load (t)
Time (S)
Speed
Distance
Load
7
6
5
4
3
2
1
0
−1
939
940
941
942
943
944
945
946
947
948
949


Pressure (Bar)
first
second
third
fourth
3
2.5
2
1.5
1
0.5
0
939
940
941
942
943
944
945
946
947
948
949

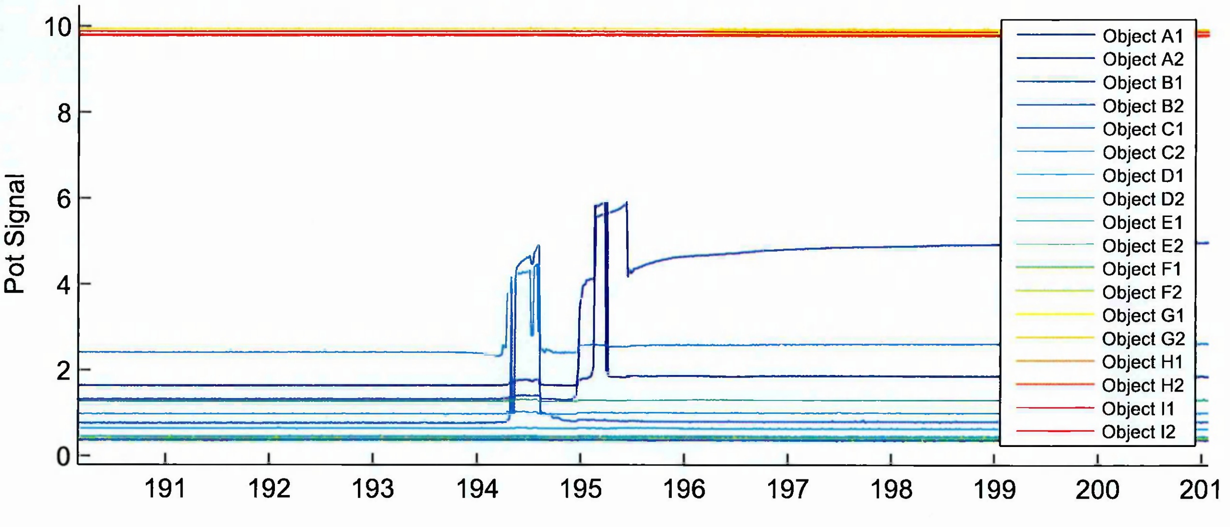

Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
10
8
6
4
2
0
939
940
941
942
943
944
945
946
947
948
949



Pots + Bones #3 / Inflation 1.0 bar + Load 2.8 tonnes (1)
Speed
Distance
Load
Speed (m/s), Distance (m), Load (t)
Time (S)

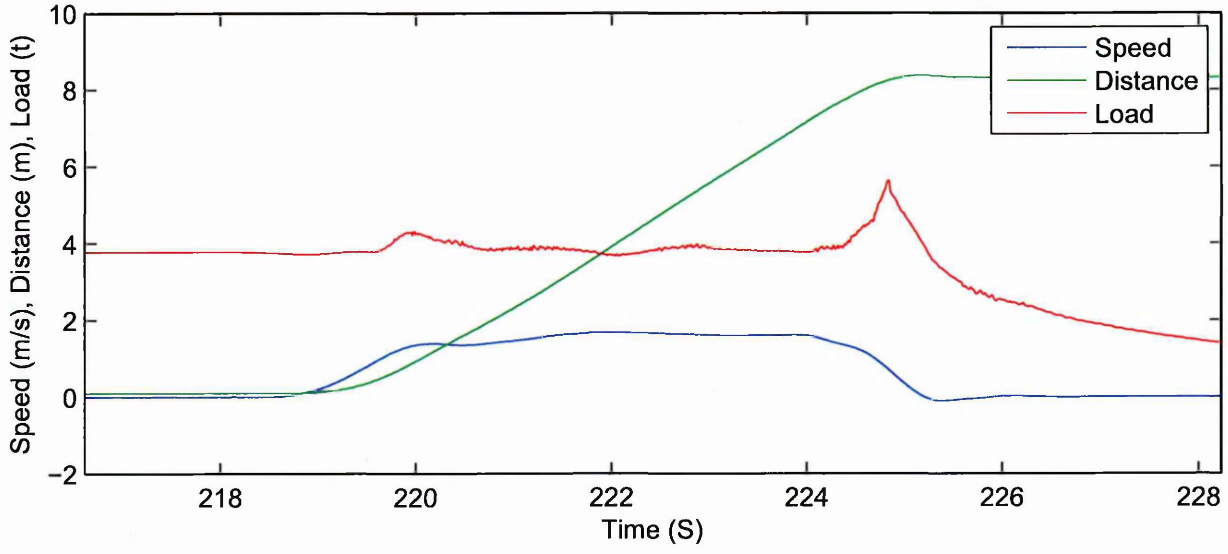


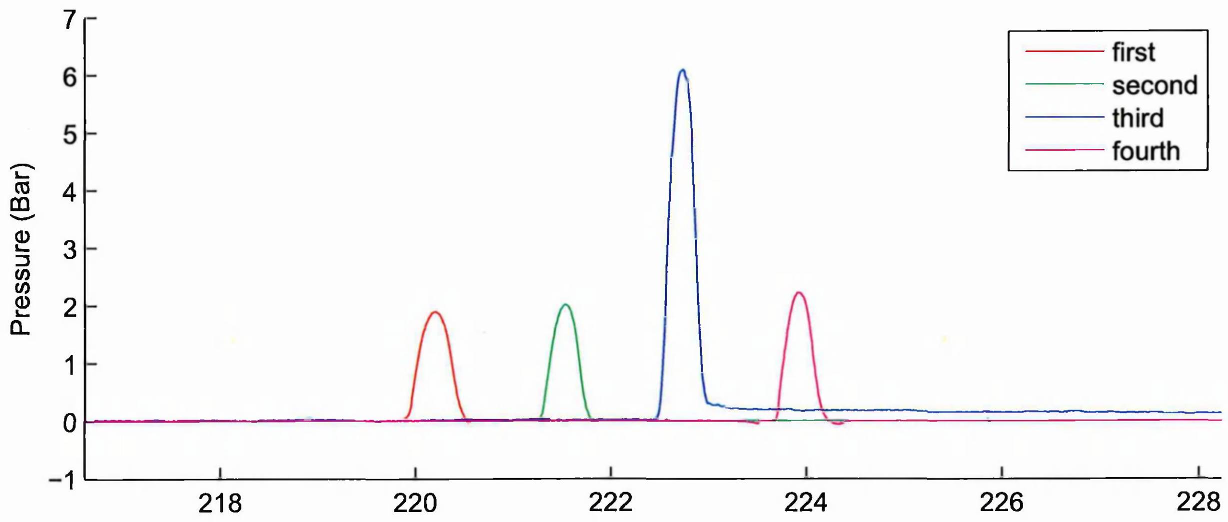
first
second
third
fourth
Pressure (Bar)

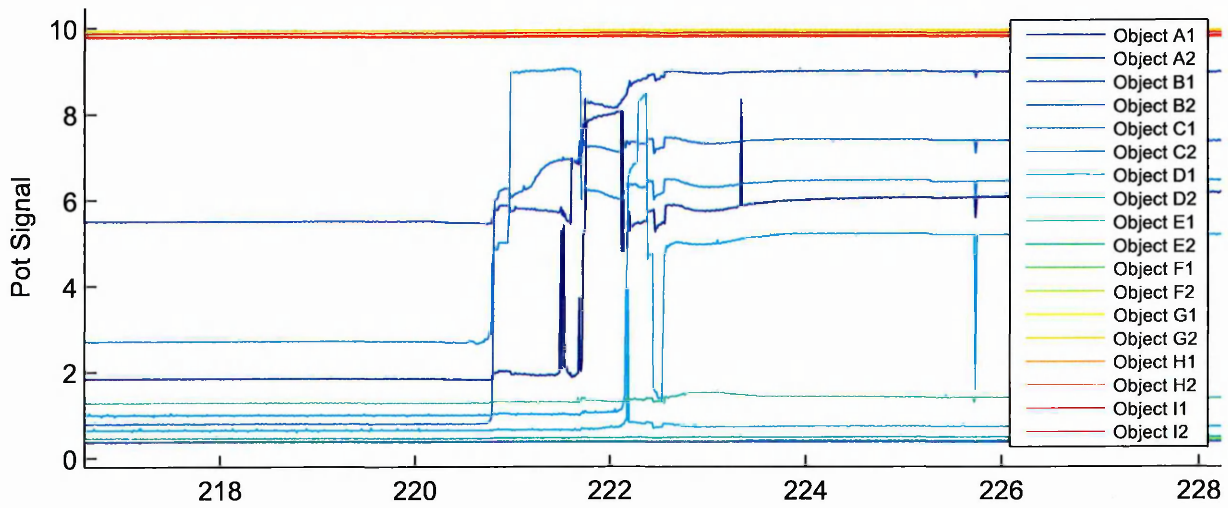


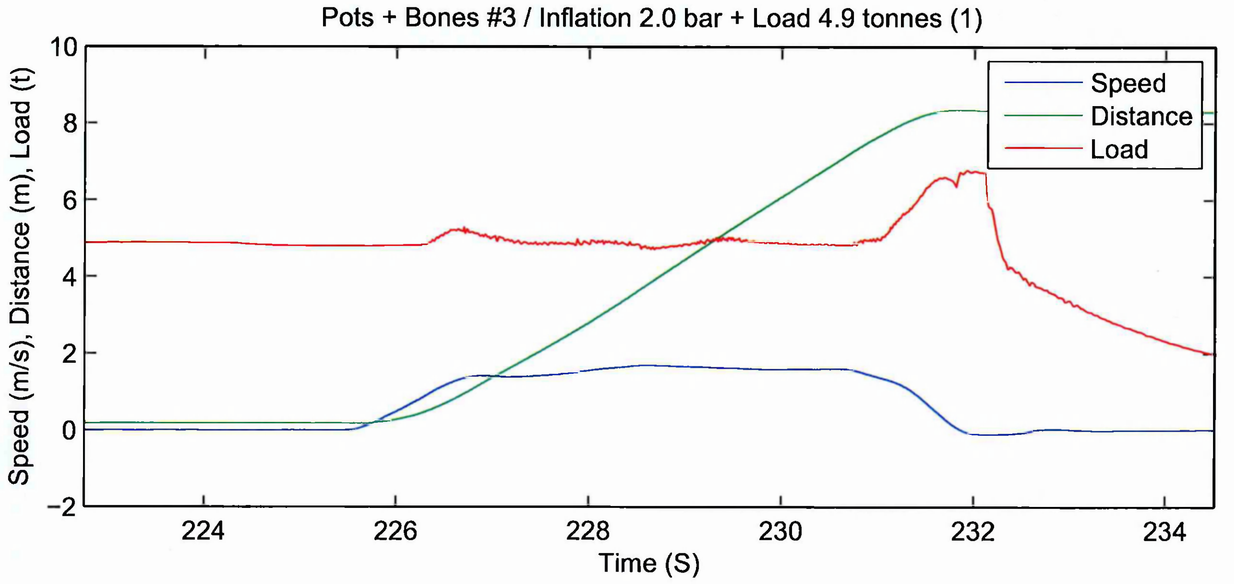
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
Pot Signal

Pots + Bones #3 / Inflation 1.5 bar + Load 3.8 tonnes (1)

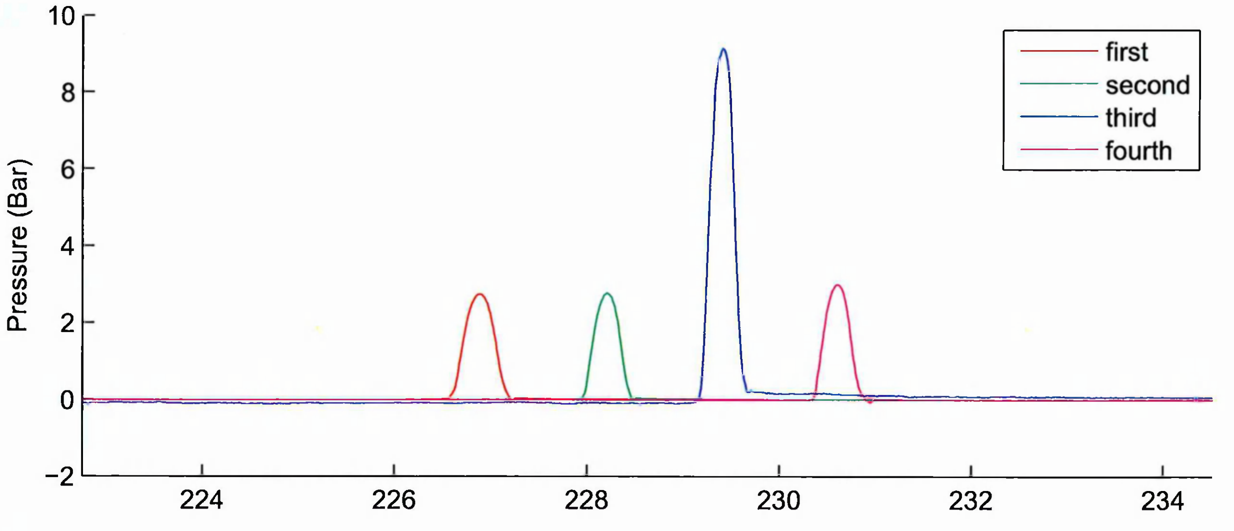




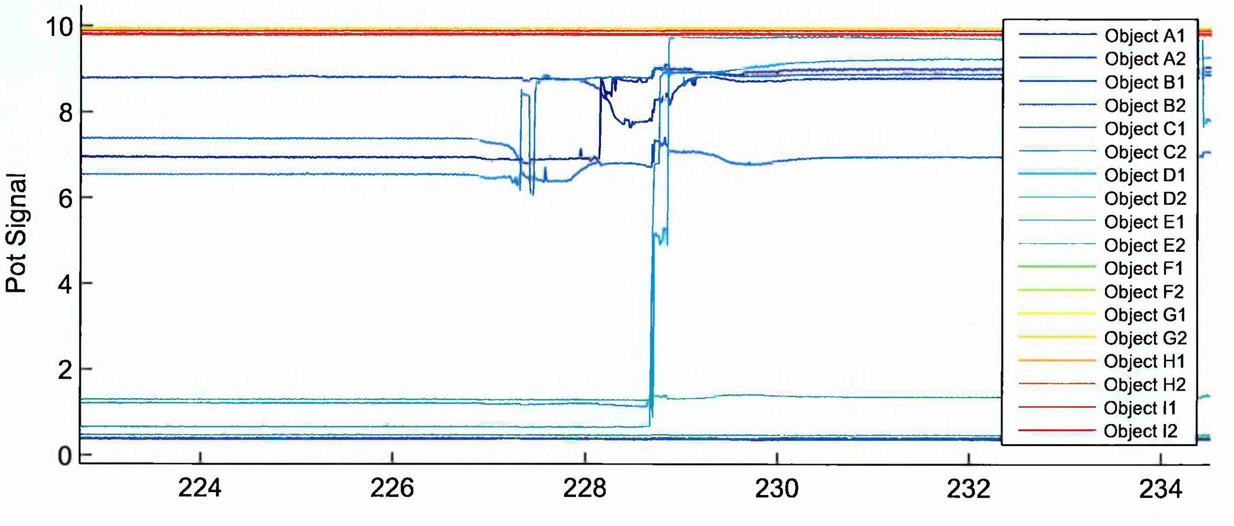




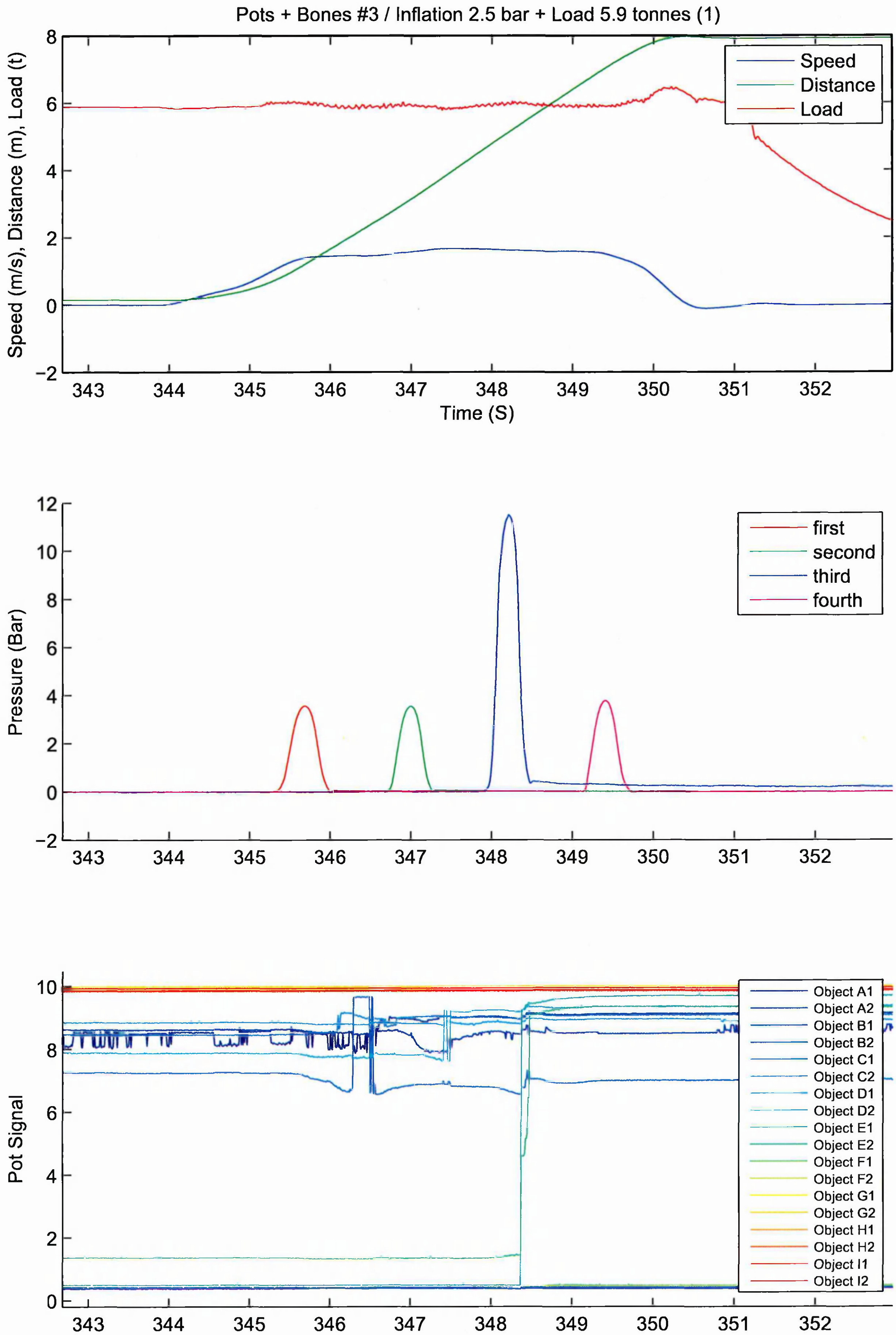
Pots + Bones #3 / Inflation 2.0 bar + Load 4.9 tonnes (1)
Speed
Distance
Load
Speed (m/s), Distance (m), Load (t)
Time (S)



first
second
third
fourth
Pressure (Bar)

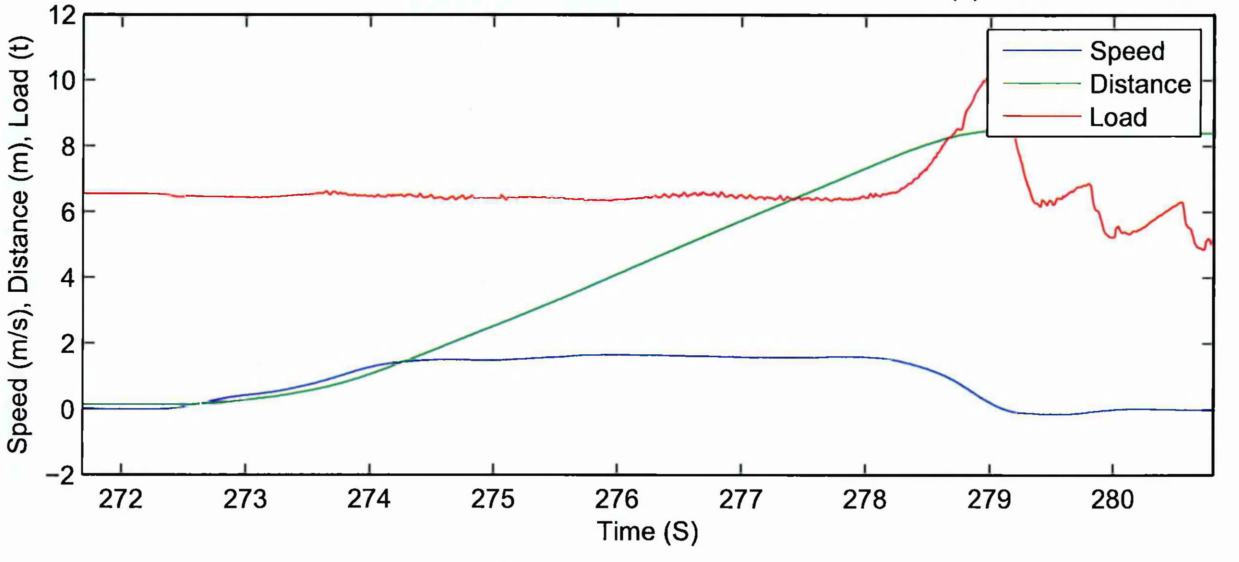


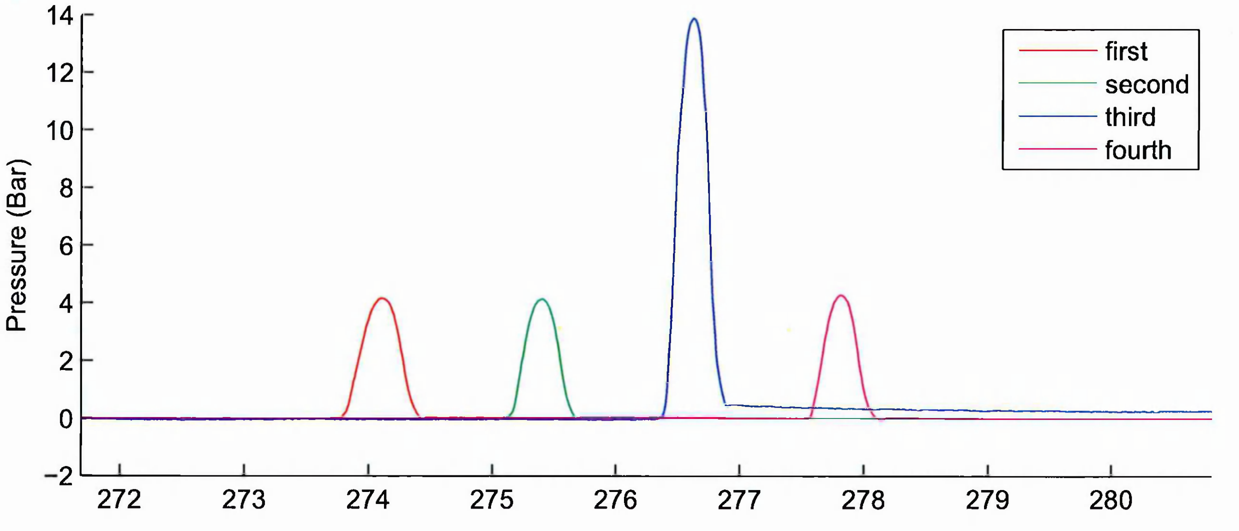
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
Pot Signal

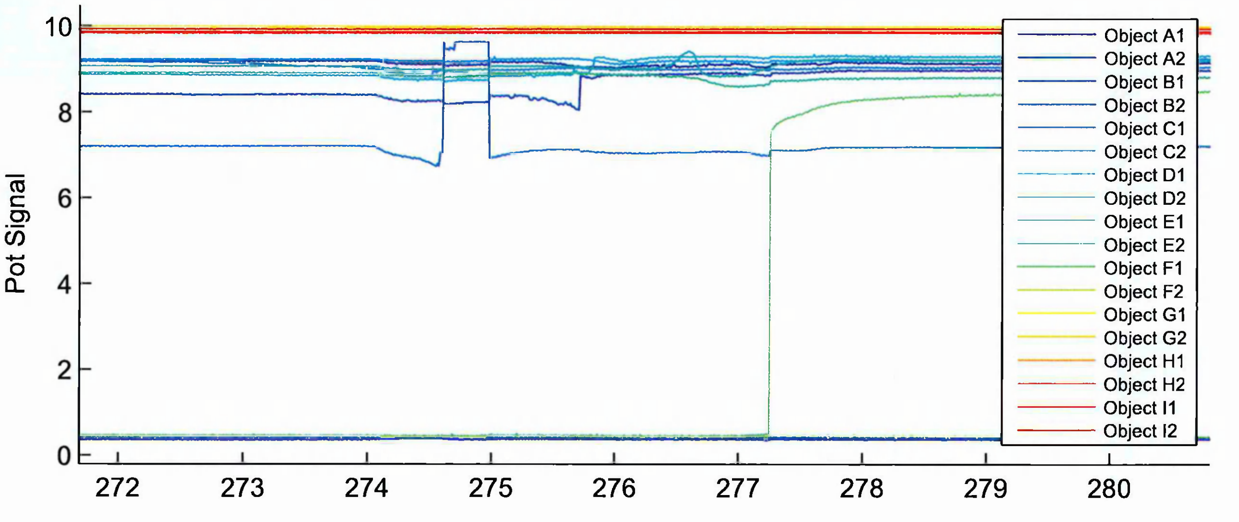


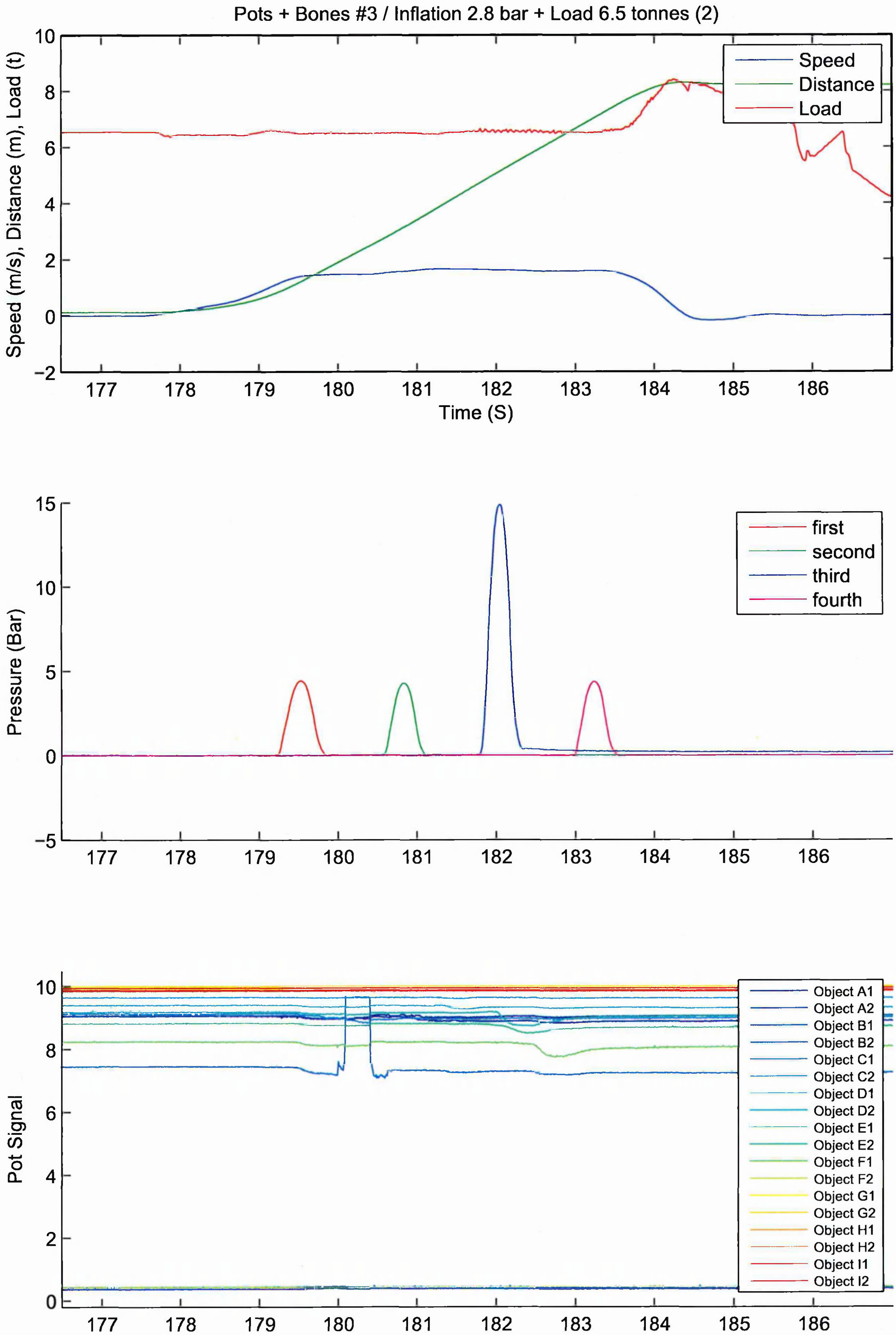
Pots + Bones #3 / Inflation 2.5 bar + Load 5.9 tonnes (1)
Speed (m/s), Distance (m), Load (t)
Speed
Distance
Load
Time (S)
Pressure (Bar)
first
second
third
fourth
Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2

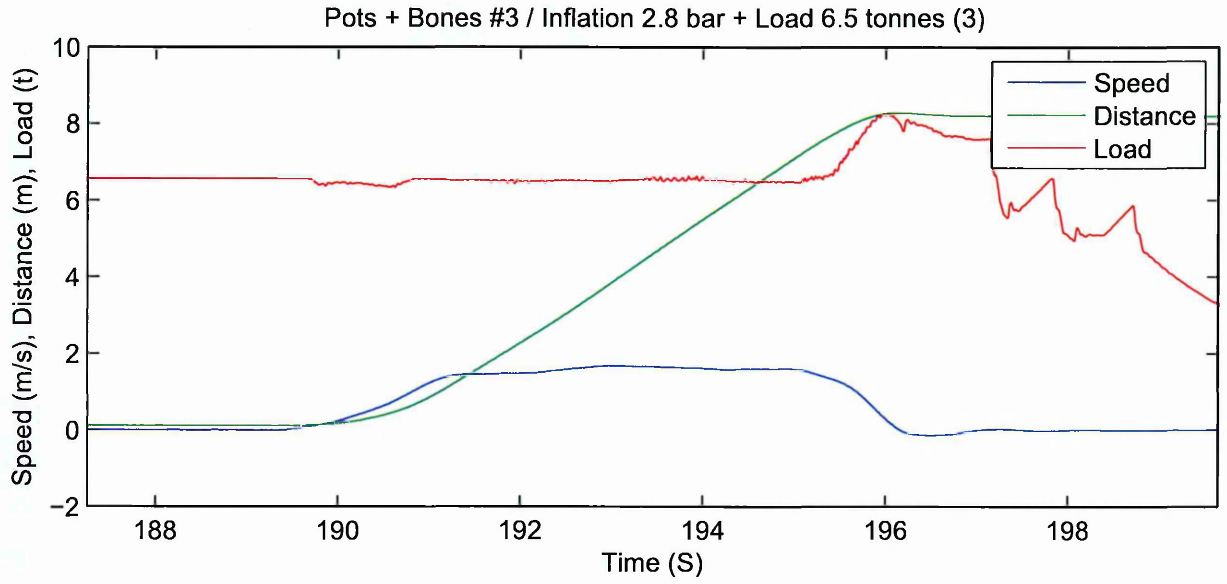
Pots + Bones #3 / Inflation 2.8 bar + Load 6.5 tonnes (1)

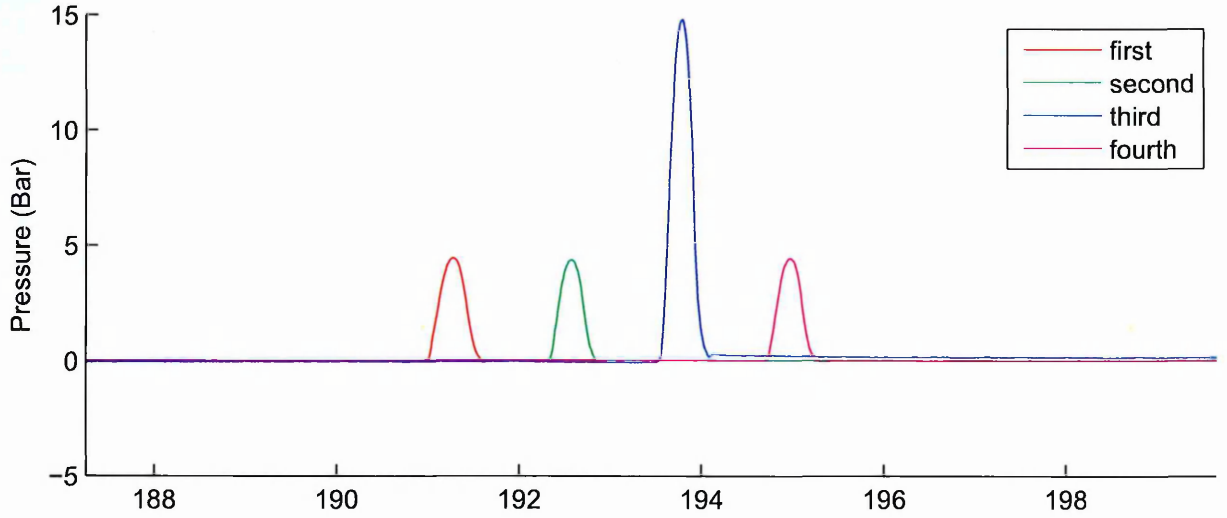


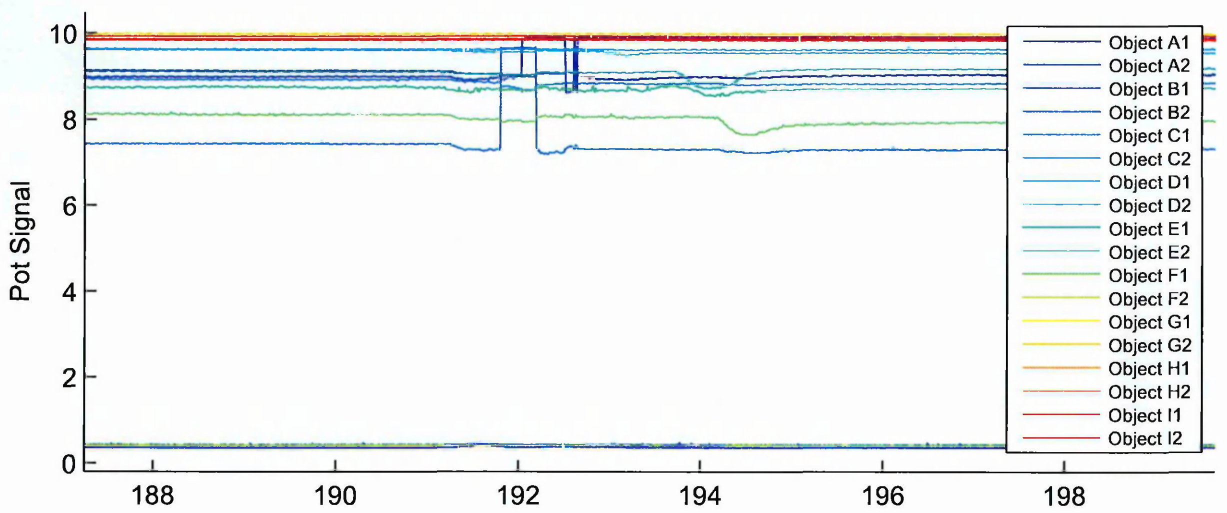


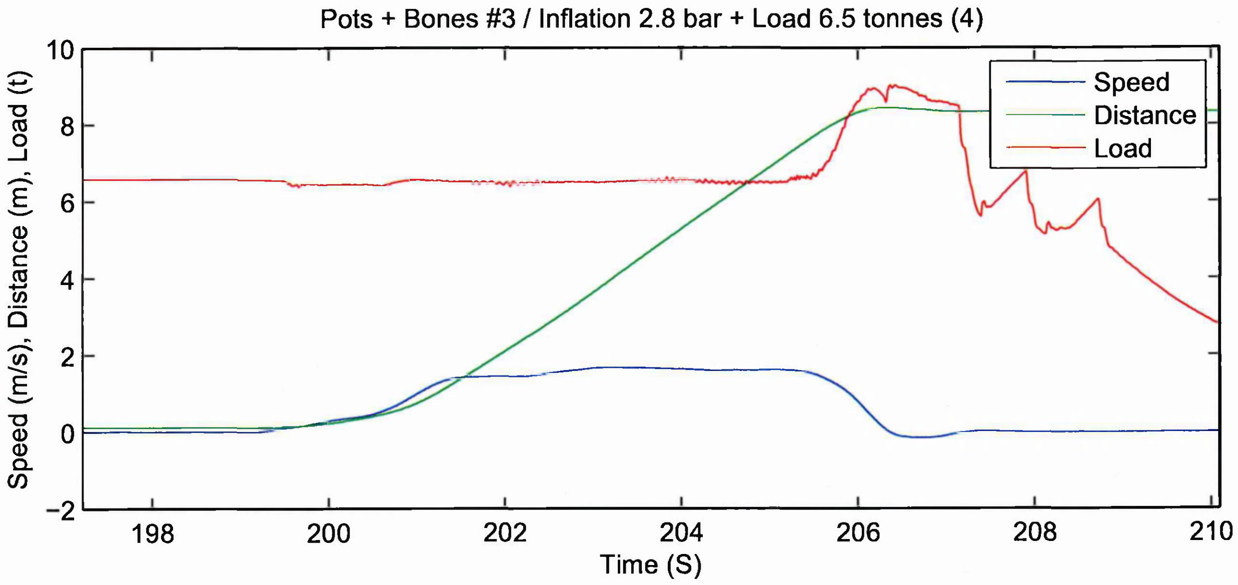


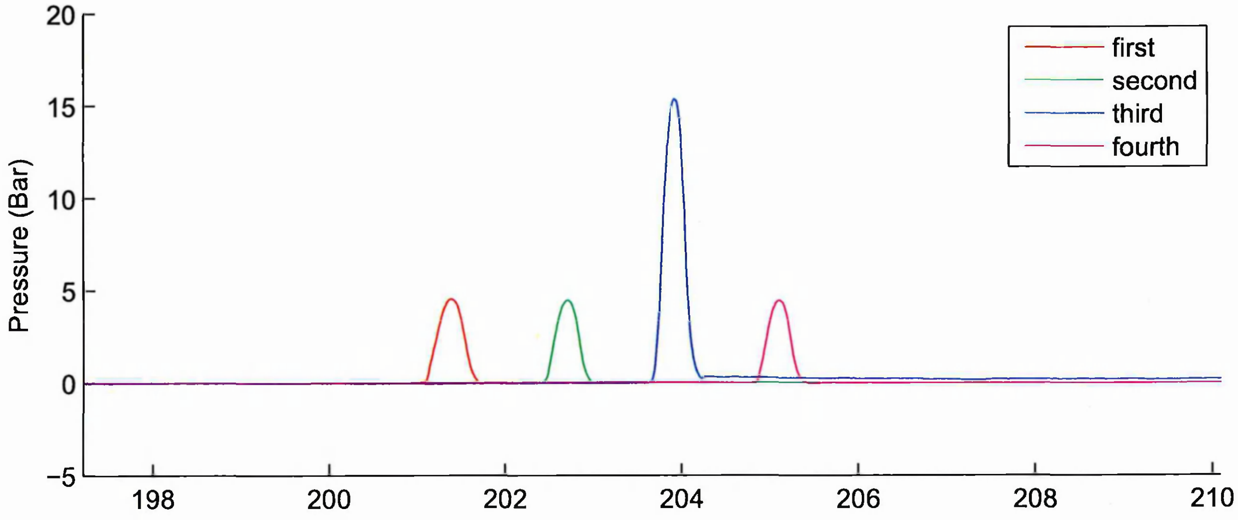

Pots + Bones #3 / Inflation 2.8 bar + Load 6.5 tonnes (2)
Speed (m/s), Distance (m), Load (t)
Speed
Distance
Load
Time (S)
177
178
179
180
181
182
183
184
185
186
Pressure (Bar)
first
second
third
fourth
Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2

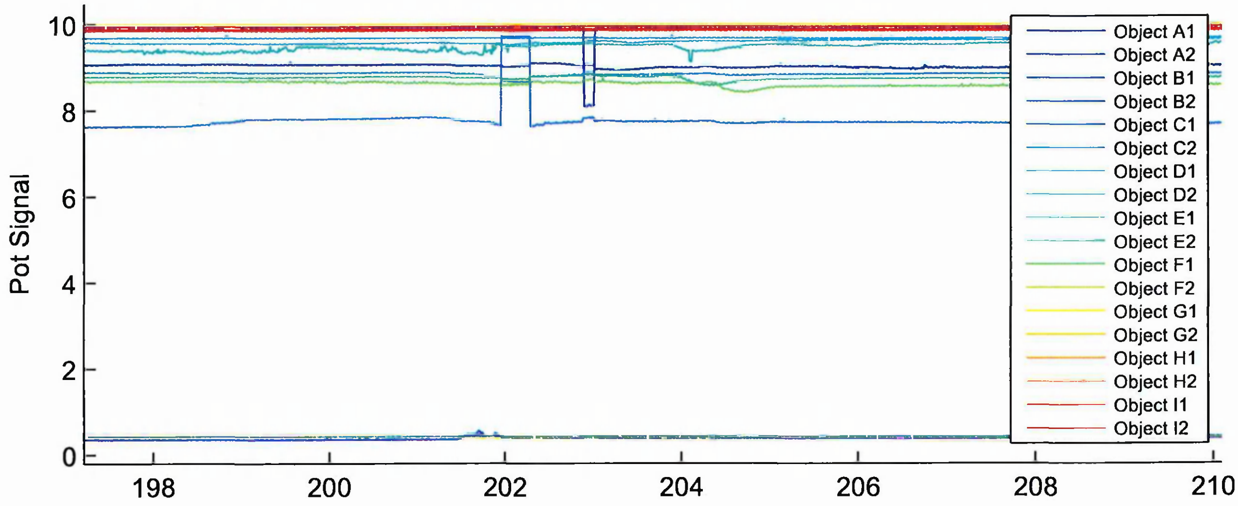

Pots + Bones #3 / Inflation 2.8 bar + Load 6.5 tonnes (3)
Speed
Distance
Load
Speed (m/s), Distance (m), Load (t)
Time (S)


first
second
third
fourth
Pressure (Bar)

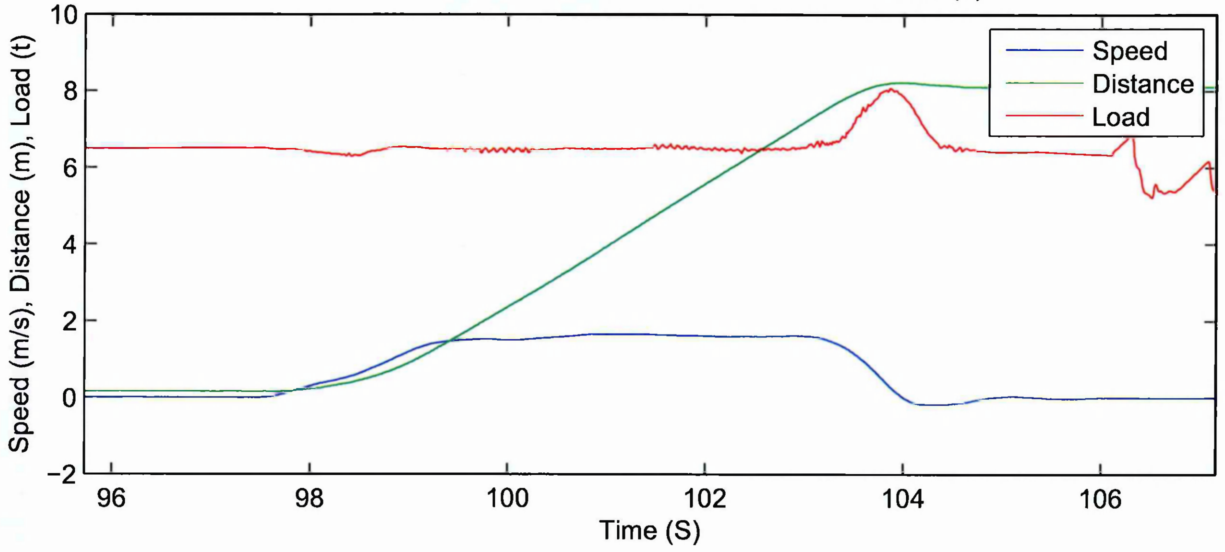

Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
Pot Signal

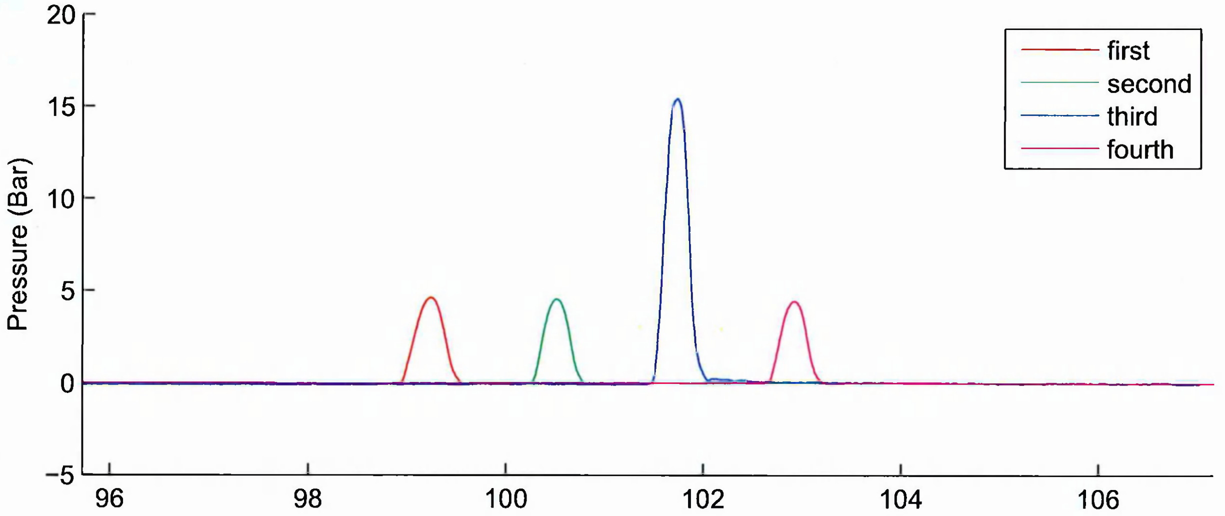

Pots + Bones #3 / Inflation 2.8 bar + Load 6.5 tonnes (4)
Speed (m/s), Distance (m), Load (t)
Time (S)
Speed
Distance
Load
10
8
6
4
2
0
-2
198
200
202
204
206
208
210

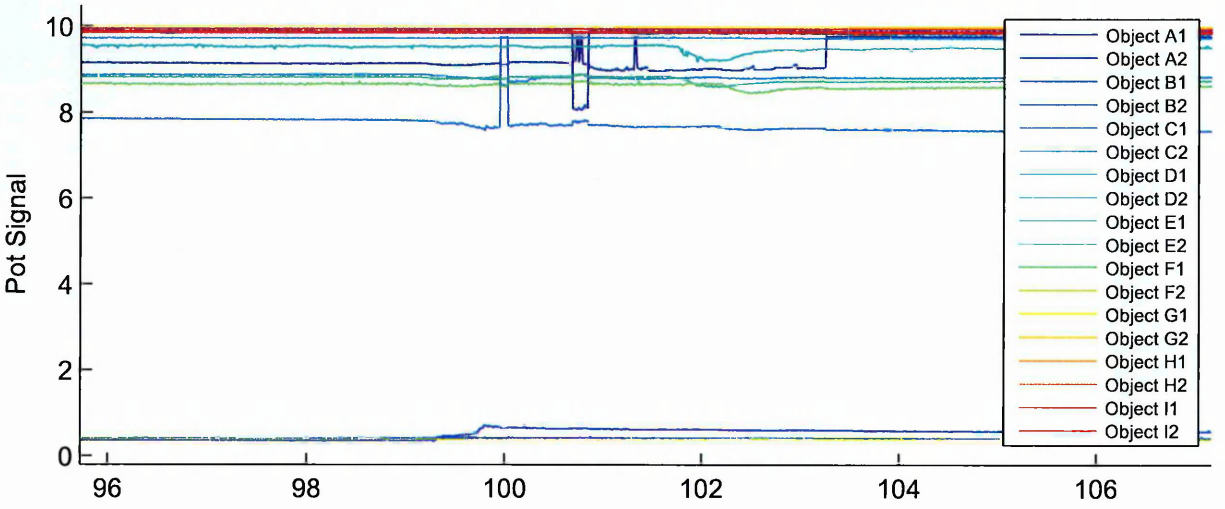

Pressure (Bar)
first
second
third
fourth
20
15
10
5
0
-5
198
200
202
204
206
208
210


Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
10
8
6
4
2
0
198
200
202
204
206
208
210

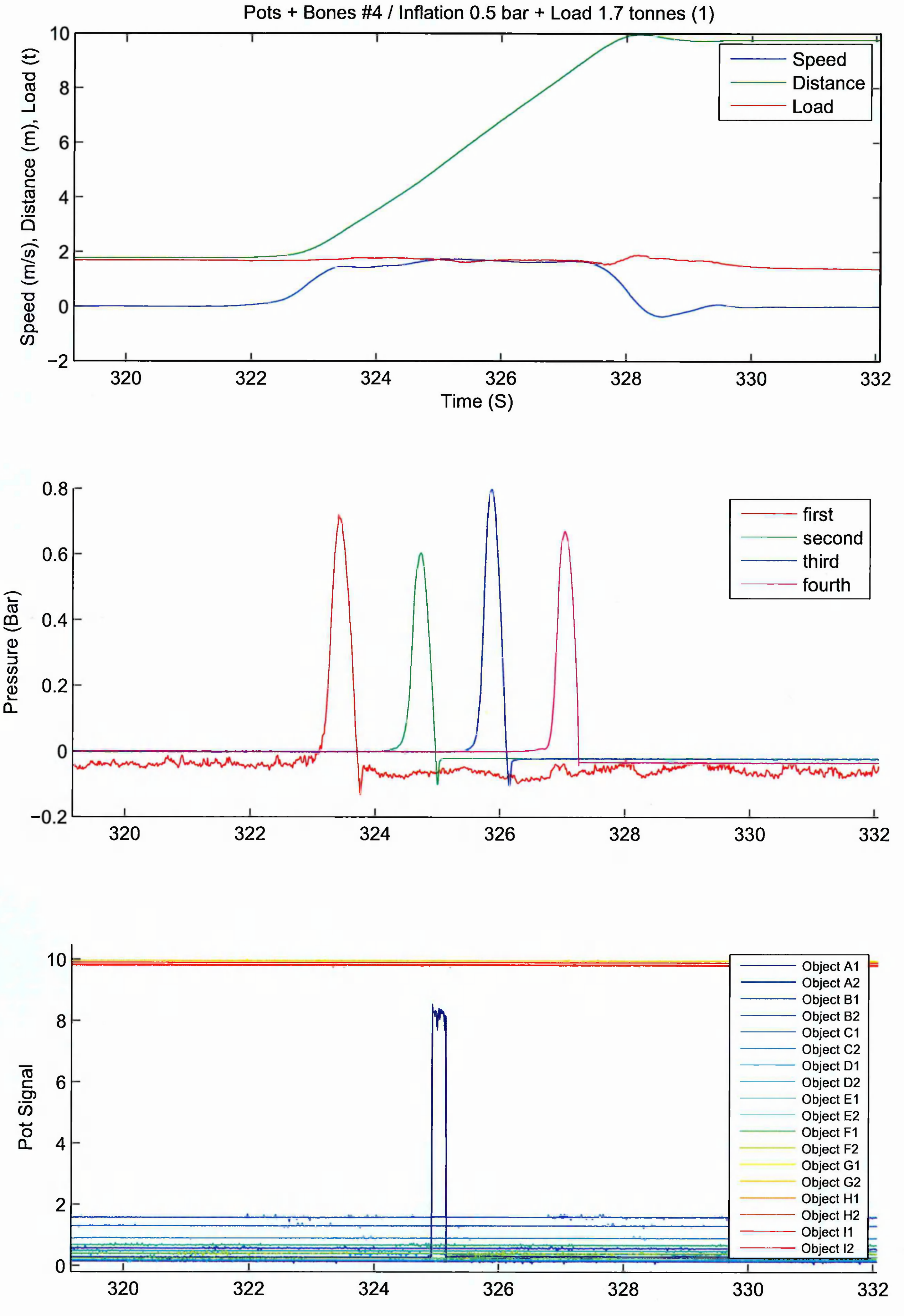
Pots + Bones #3 / Inflation 2.8 bar + Load 6.5 tonnes (5)



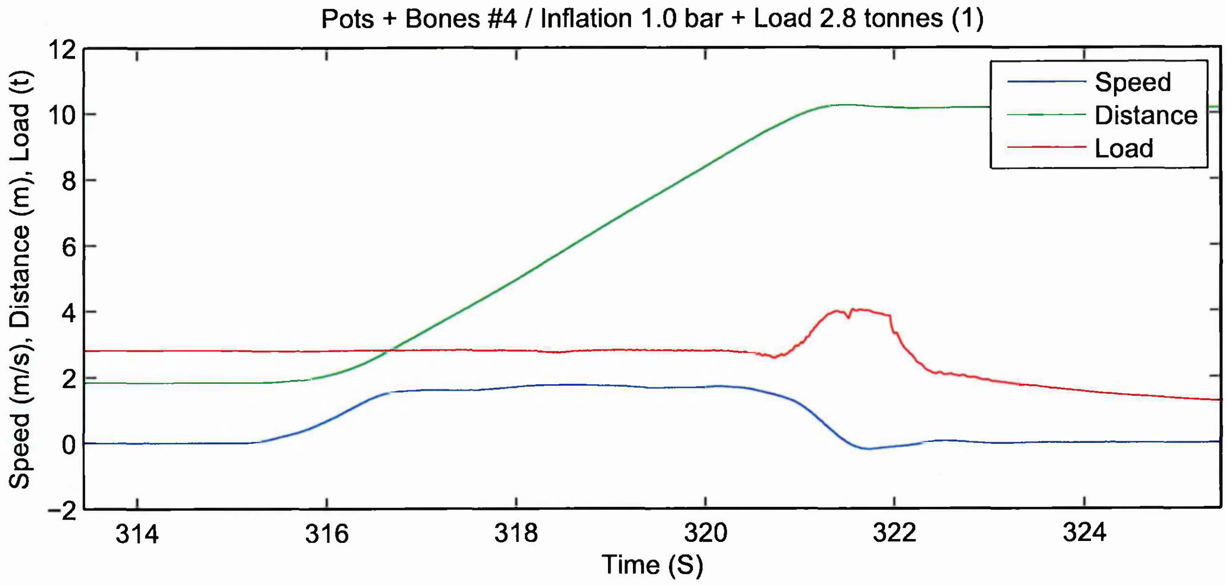




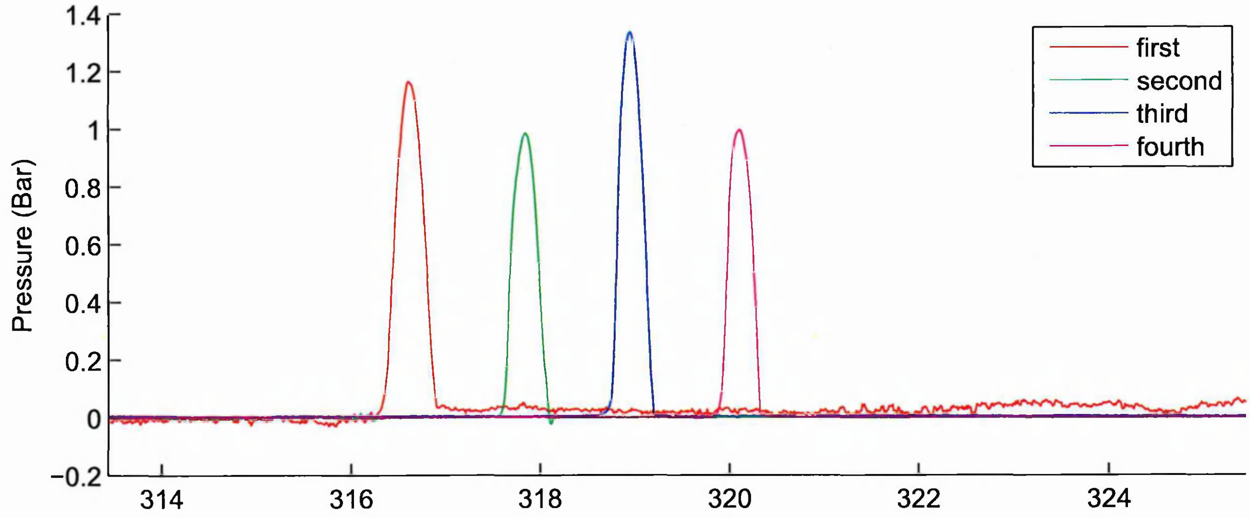
R4	R4
Object A1	bone perpendicular ?
Object A2	bone perpendicular ?
Object B1	flint beaker rim
Object B2	flint beaker body
Object C1	roman thrown body
Object C2	roman thrown rim
Object D1	bone parallel ?
Object D2	bone parallel ?
Object E1	sand + flint tempered rim
Object E2	sand + flint tempered body
Object F1	shell tempered rim
Object F2	shell tempered body
Object G1	X
Object G2	X
Object H1	X
Object H2	X
Object I1	X
Object I2	X



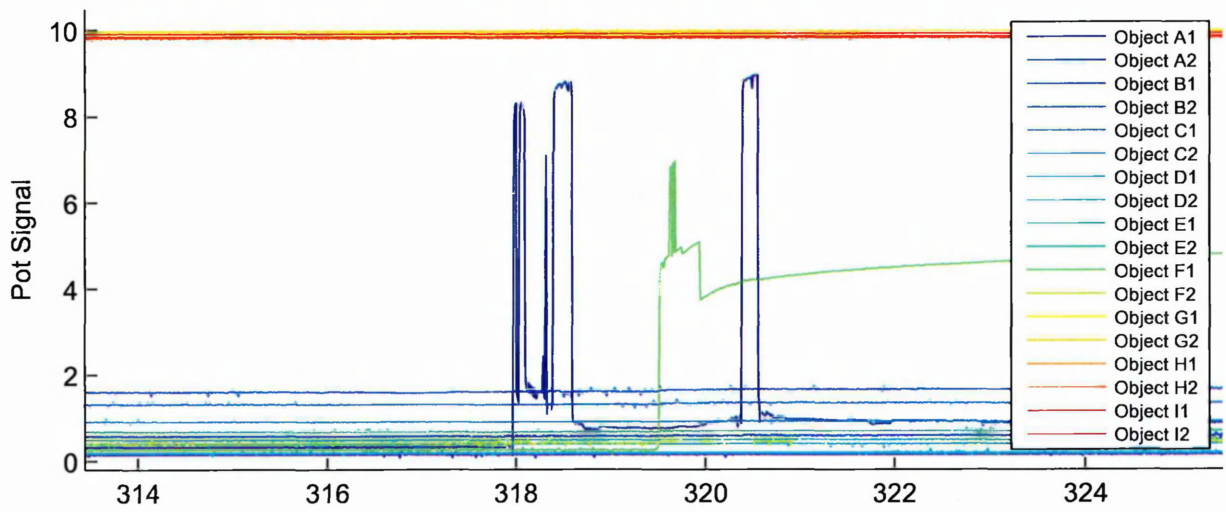
Pots + Bones #4 / Inflation 0.5 bar + Load 1.7 tonnes (1)
Speed (m/s), Distance (m), Load (t)
Speed
Distance
Load
Time (S)
Pressure (Bar)
first
second
third
fourth
Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2



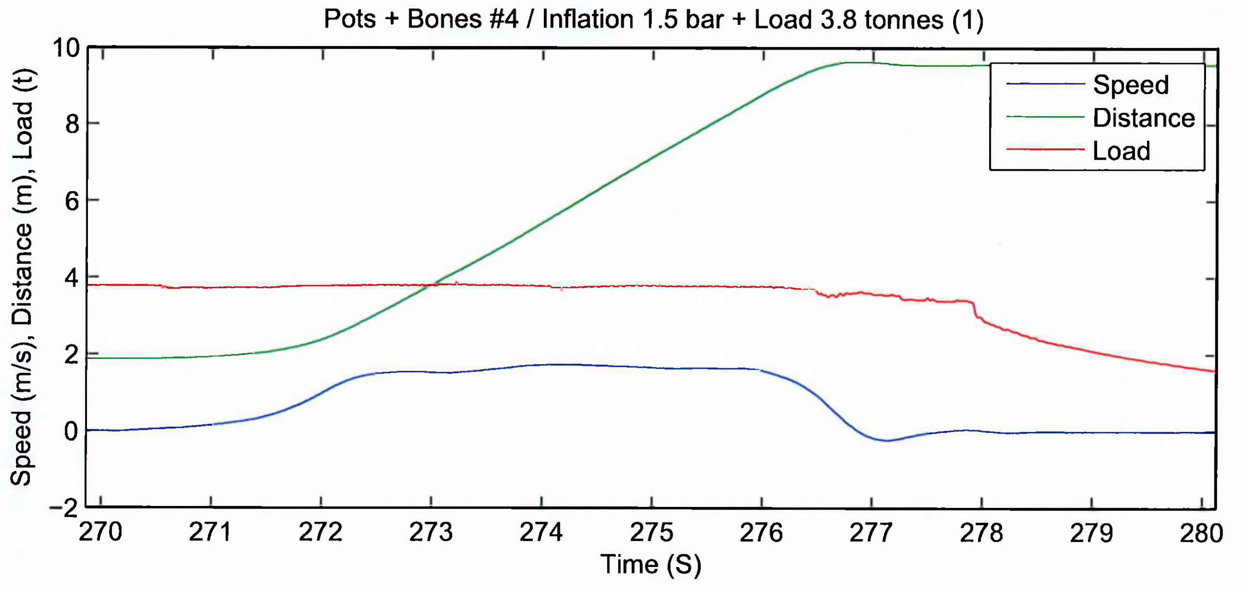
Pots + Bones #4 / Inflation 1.0 bar + Load 2.8 tonnes (1)
Speed
Distance
Load
Speed (m/s), Distance (m), Load (t)
Time (S)
-2
0
2
4
6
8
10
12
314
316
318
320
322
324



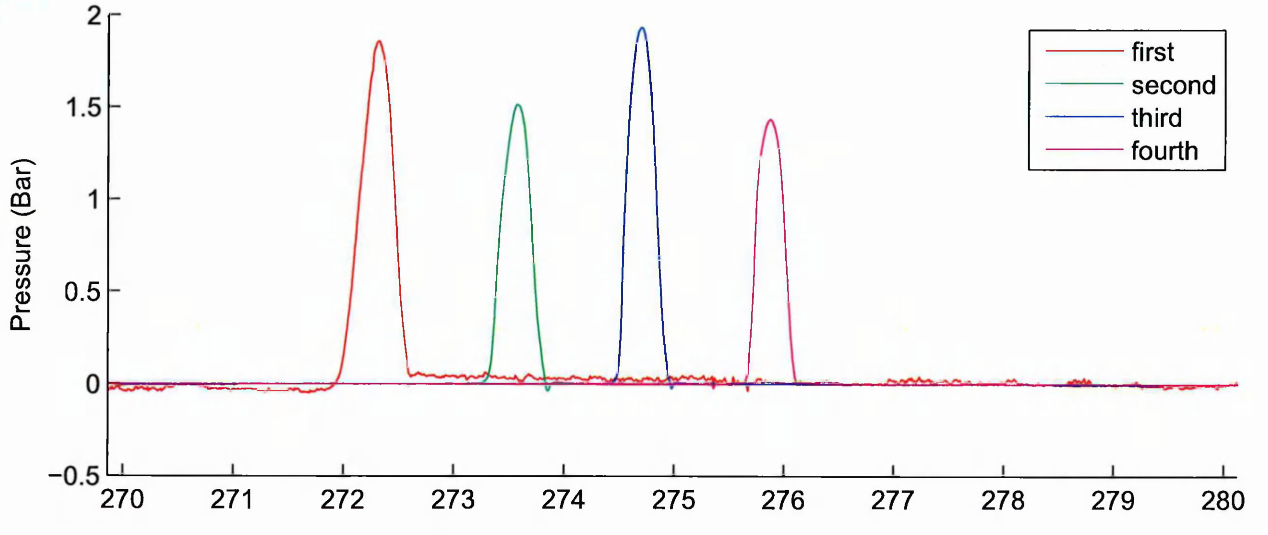
first
second
third
fourth
Pressure (Bar)
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
314
316
318
320
322
324



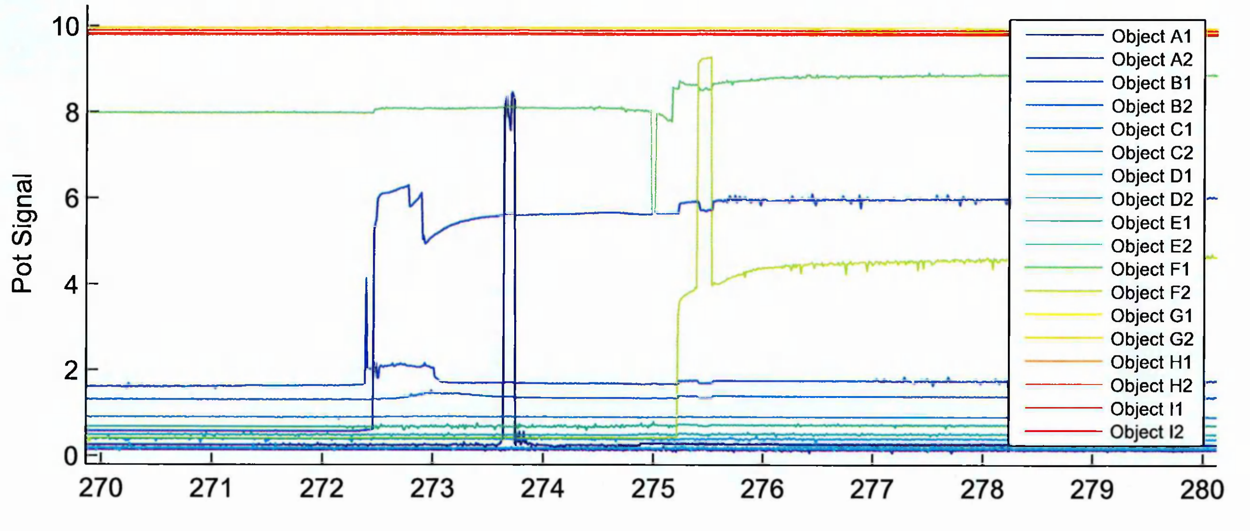
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
Pot Signal
0
2
4
6
8
10
314
316
318
320
322
324



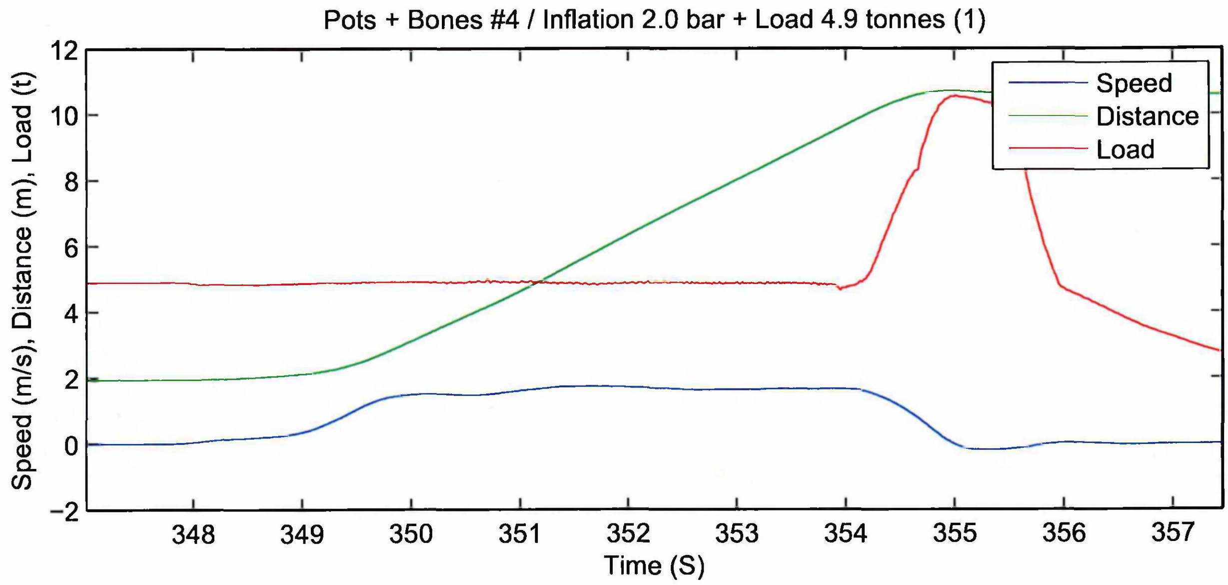
Pots + Bones #4 / Inflation 1.5 bar + Load 3.8 tonnes (1)
Speed
Distance
Load
Speed (m/s), Distance (m), Load (t)
Time (S)
10
8
6
4
2
0
-2
270
271
272
273
274
275
276
277
278
279
280

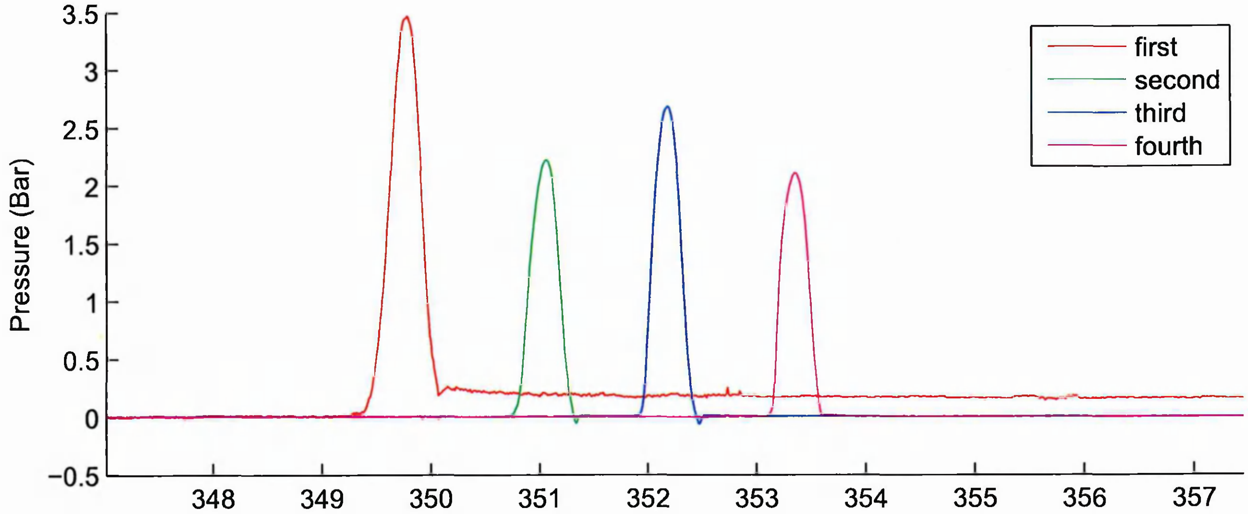


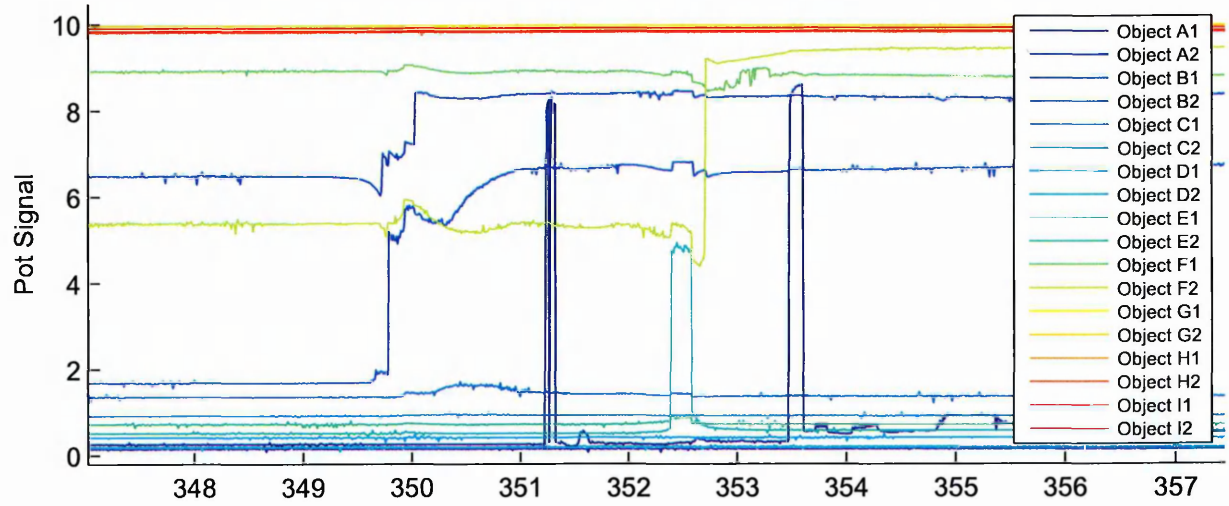
first
second
third
fourth
Pressure (Bar)
2
1.5
1
0.5
0
-0.5
270
271
272
273
274
275
276
277
278
279
280

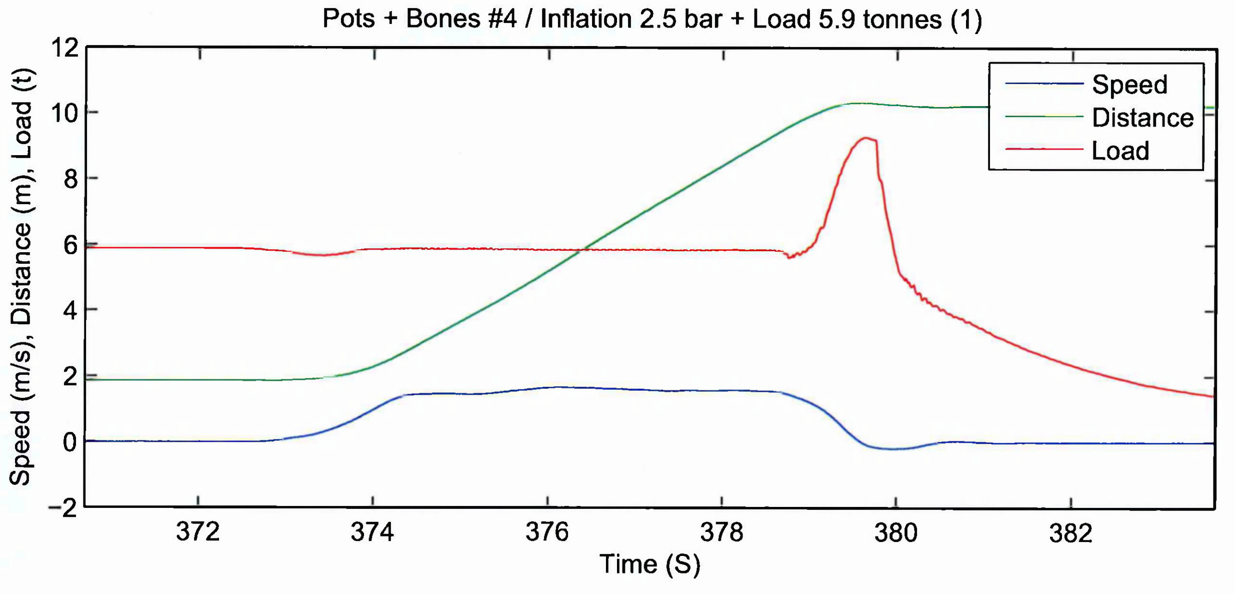


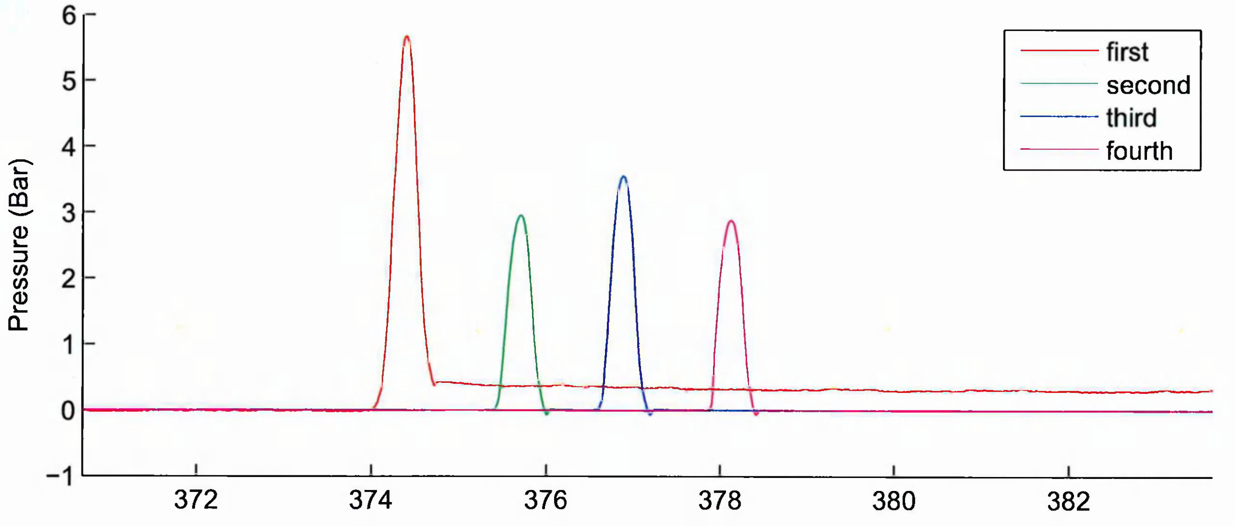
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
Pot Signal
10
8
6
4
2
0
270
271
272
273
274
275
276
277
278
279
280

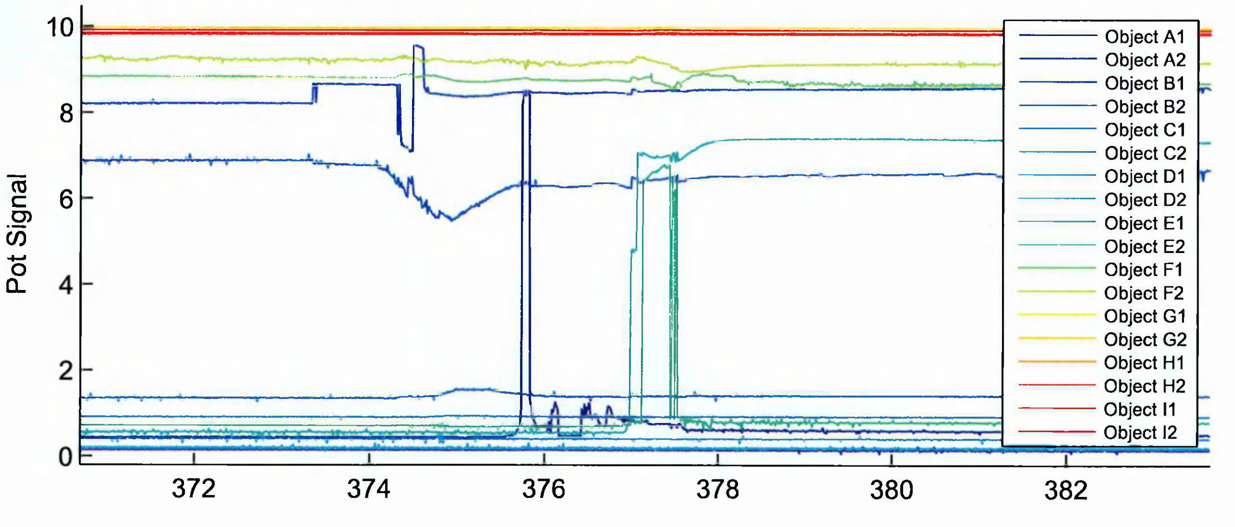

Pots + Bones #4 / Inflation 2.0 bar + Load 4.9 tonnes (1)
Speed (m/s), Distance (m), Load (t)
Time (S)
Speed
Distance
Load
12
10
8
6
4
2
0
−2
348
349
350
351
352
353
354
355
356
357

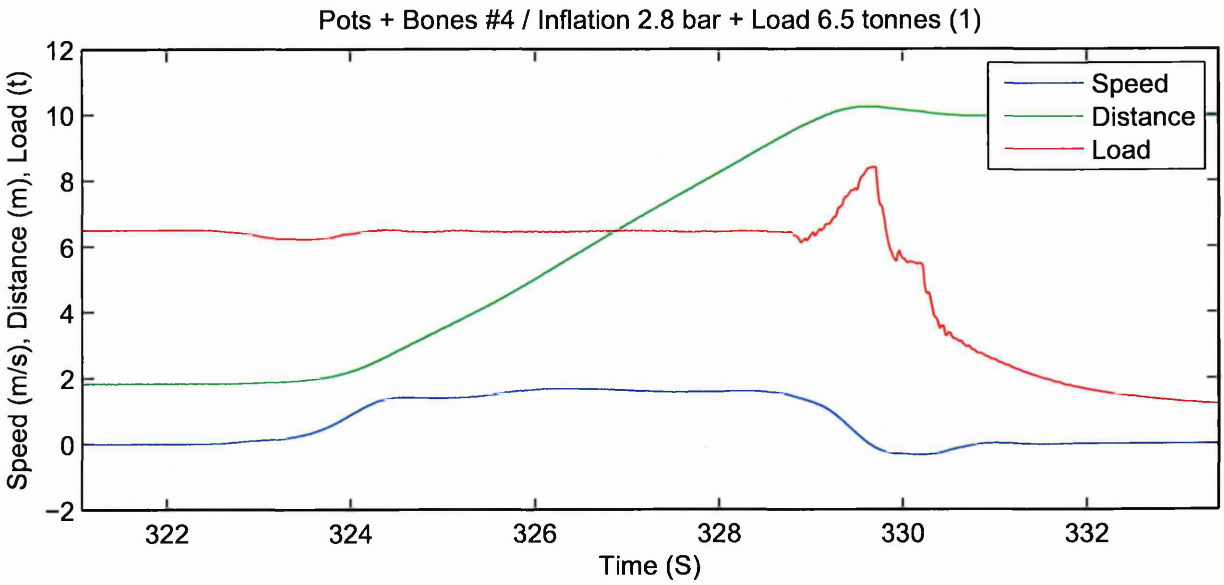

Pressure (Bar)
first
second
third
fourth
3.5
3
2.5
2
1.5
1
0.5
0
−0.5
348
349
350
351
352
353
354
355
356
357

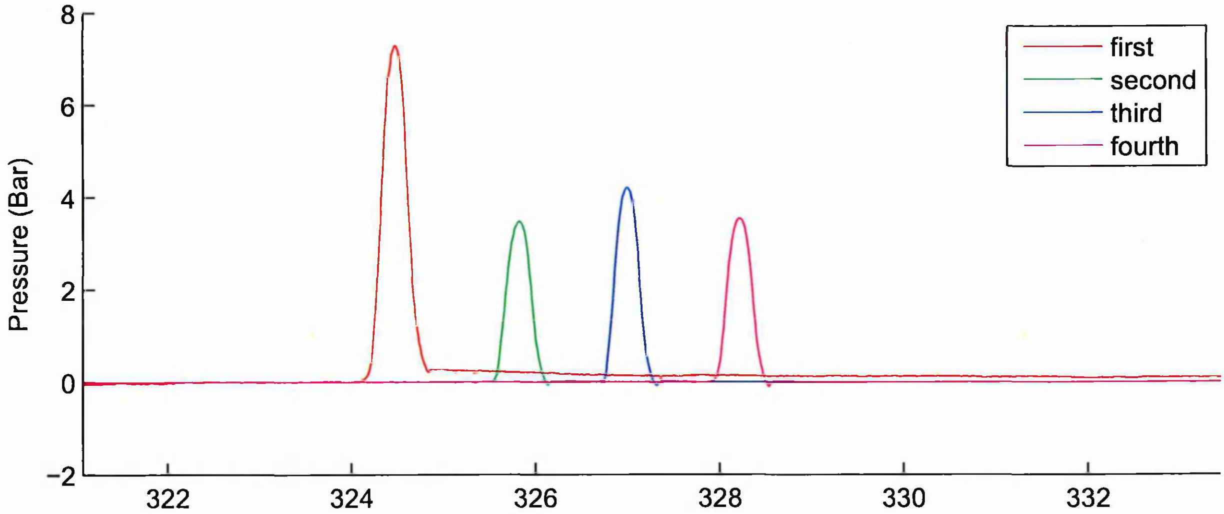

Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
10
8
6
4
2
0
348
349
350
351
352
353
354
355
356
357

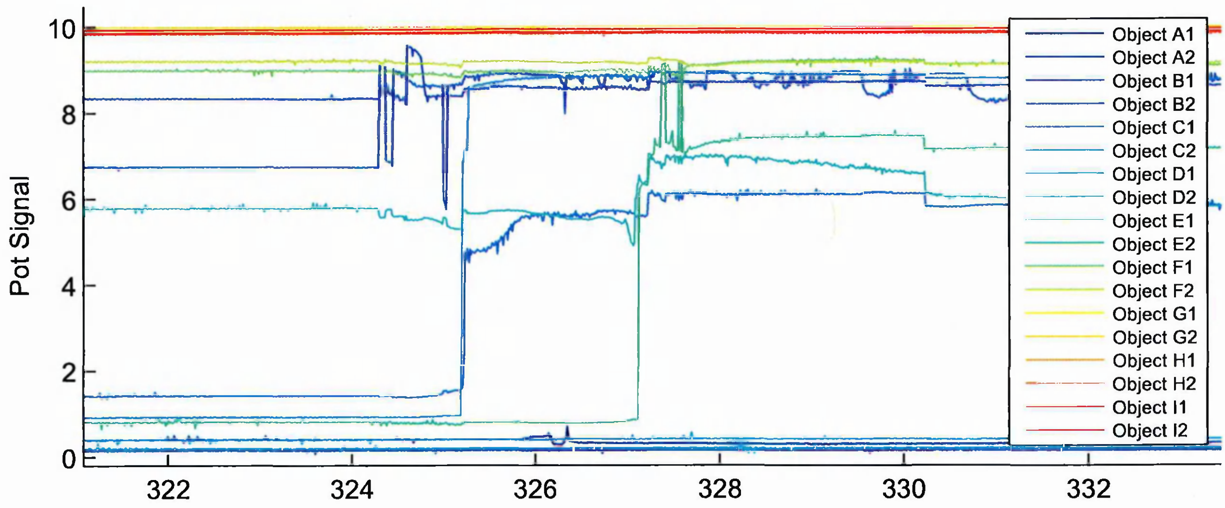

Pots + Bones #4 / Inflation 2.5 bar + Load 5.9 tonnes (1)
Speed (m/s), Distance (m), Load (t)
Time (S)
Speed
Distance
Load

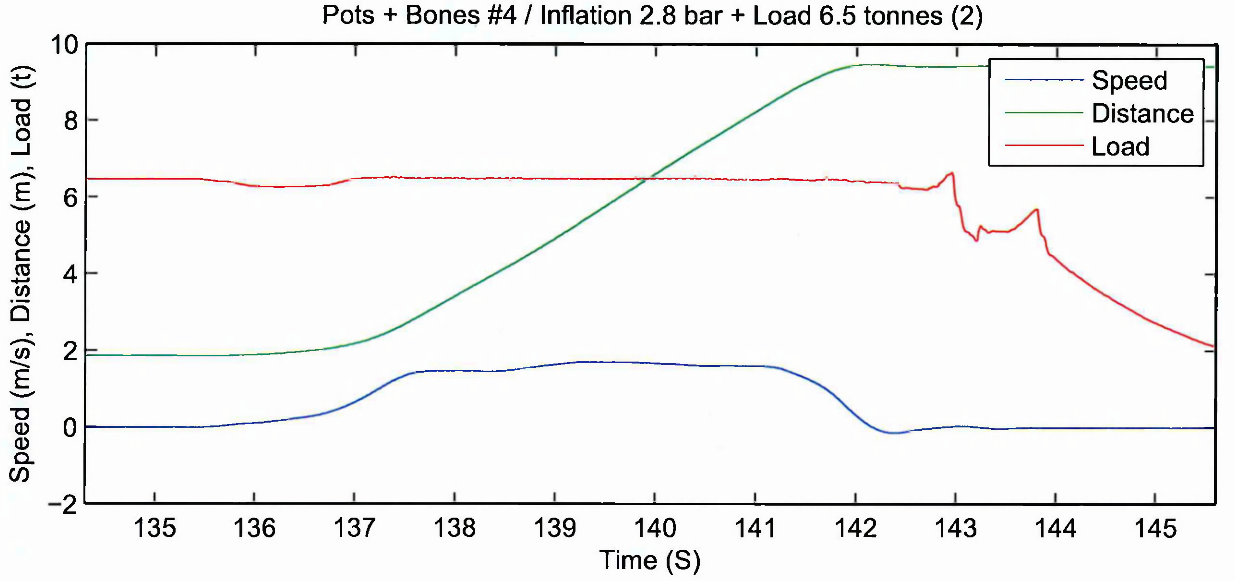

Pressure (Bar)
first
second
third
fourth

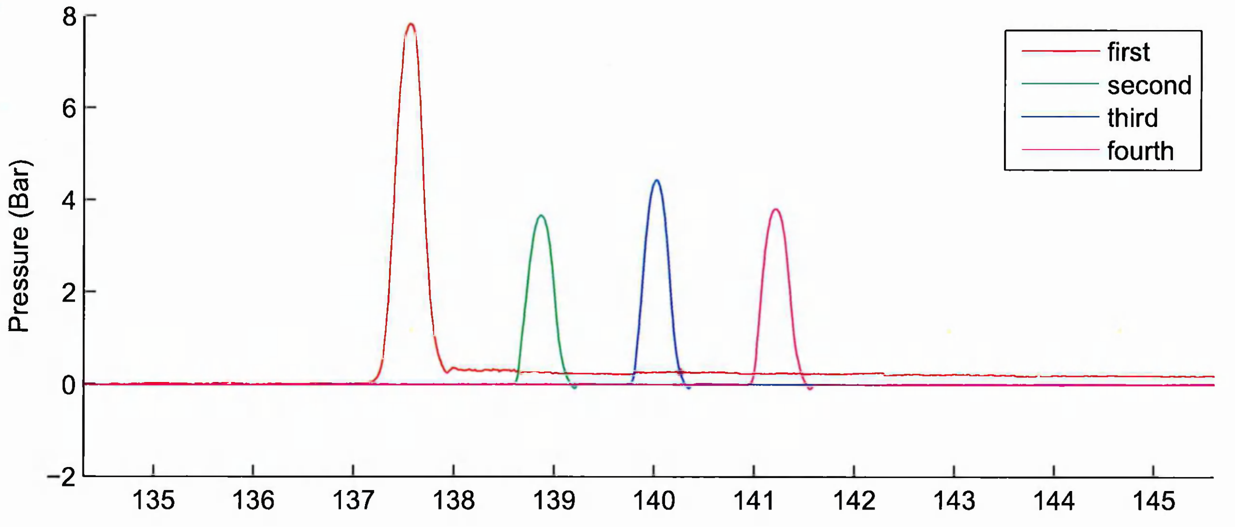

Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2

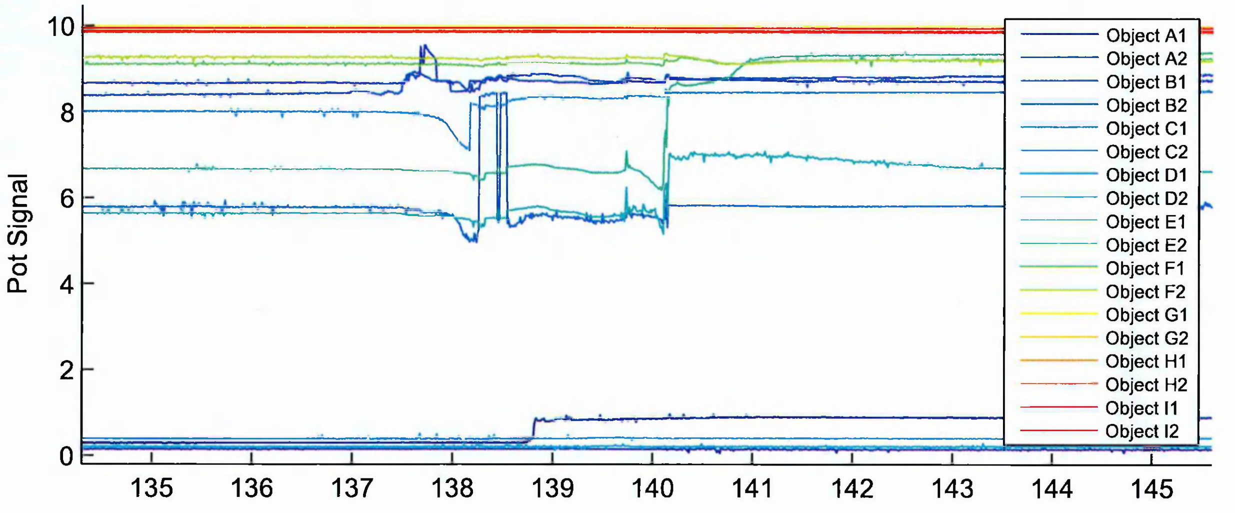

Pots + Bones #4 / Inflation 2.8 bar + Load 6.5 tonnes (1)
Speed (m/s), Distance (m), Load (t)
Time (S)
Speed
Distance
Load
12
10
8
6
4
2
0
-2
322
324
326
328
330
332

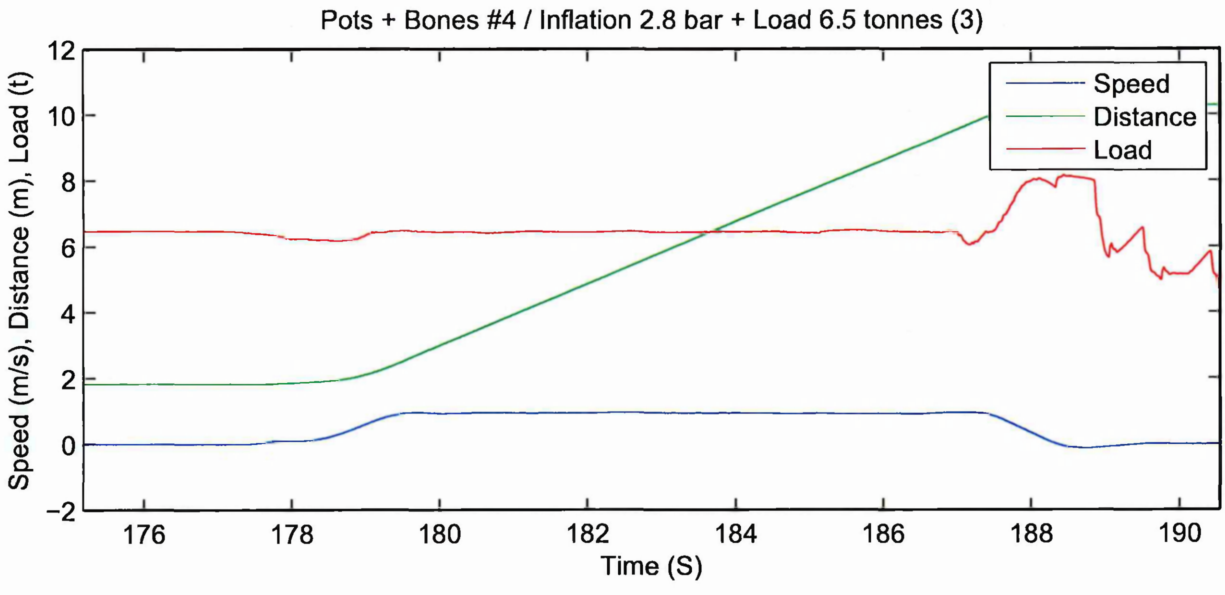

Pressure (Bar)
first
second
third
fourth
8
6
4
2
0
-2
322
324
326
328
330
332

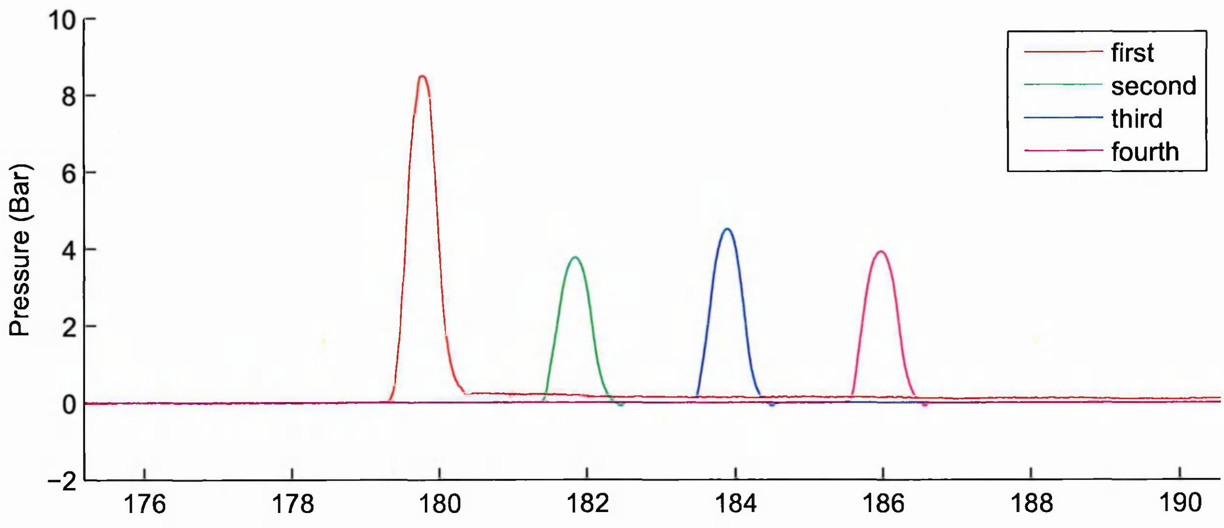

Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
10
8
6
4
2
0
322
324
326
328
330
332

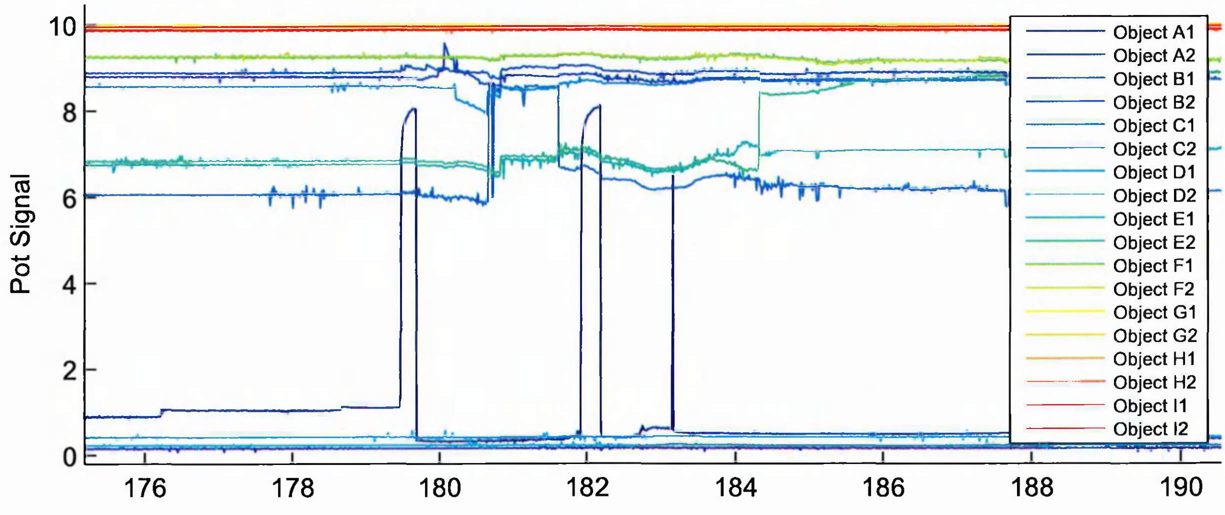

Pots + Bones #4 / Inflation 2.8 bar + Load 6.5 tonnes (2)
Speed (m/s), Distance (m), Load (t)
Time (S)
Speed
Distance
Load
10
8
6
4
2
0
-2
135
136
137
138
139
140
141
142
143
144
145

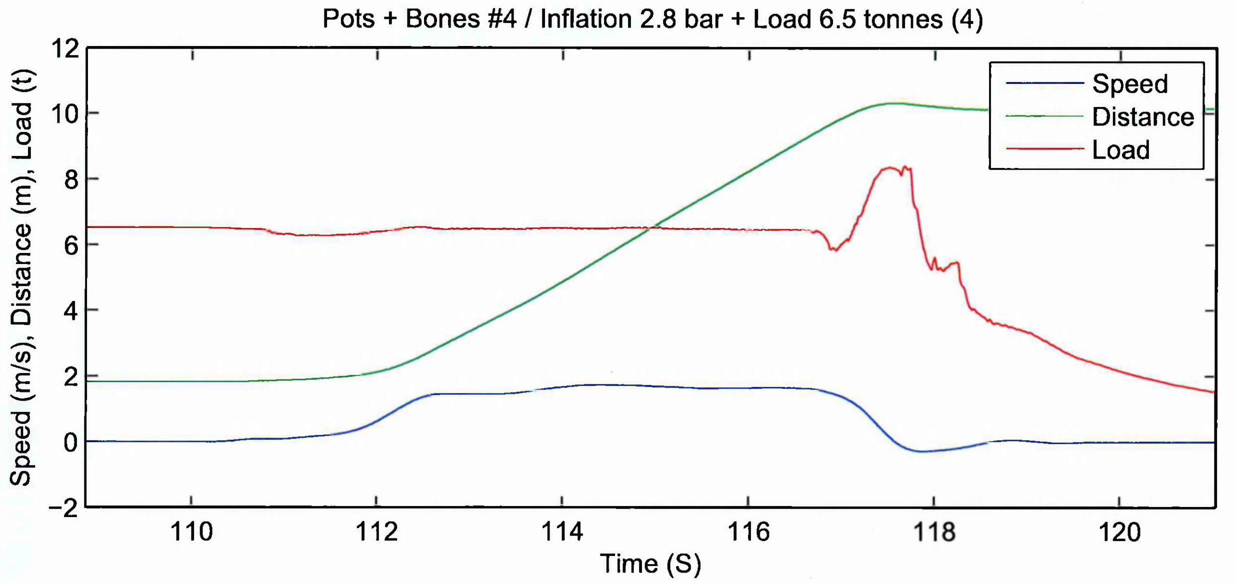

Pressure (Bar)
first
second
third
fourth
8
6
4
2
0
-2
135
136
137
138
139
140
141
142
143
144
145

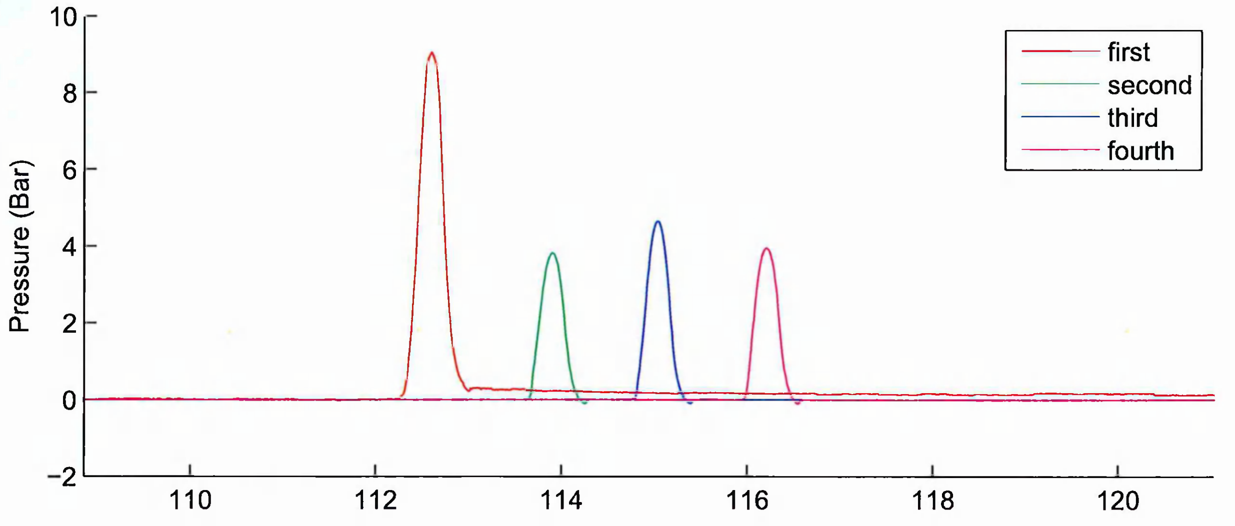

Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
10
8
6
4
2
0
135
136
137
138
139
140
141
142
143
144
145

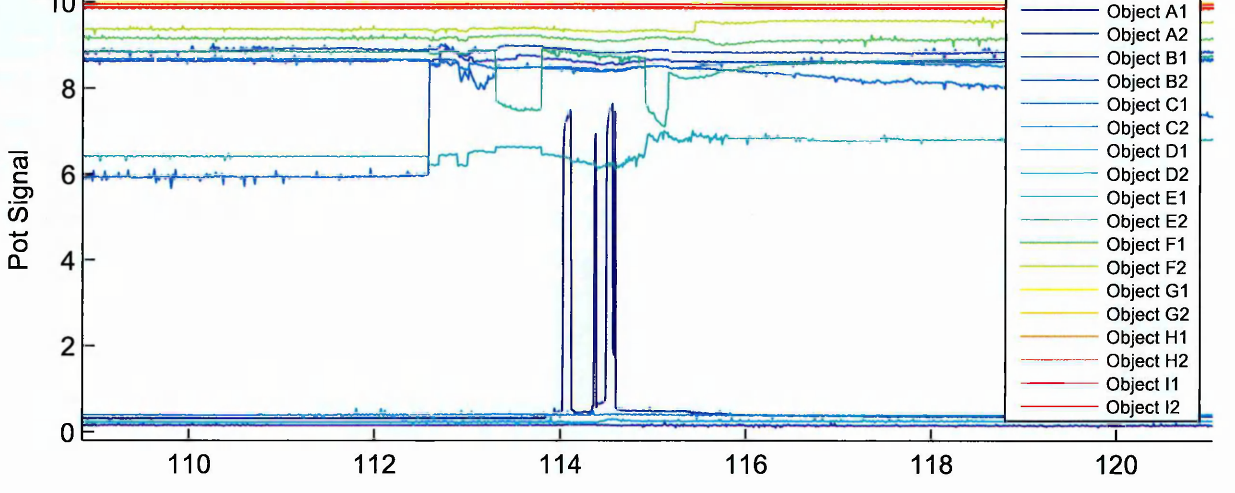

Pots + Bones #4 / Inflation 2.8 bar + Load 6.5 tonnes (3)
Speed (m/s), Distance (m), Load (t)
Time (S)
Speed
Distance
Load
12
10
8
6
4
2
0
−2
176
178
180
182
184
186
188
190

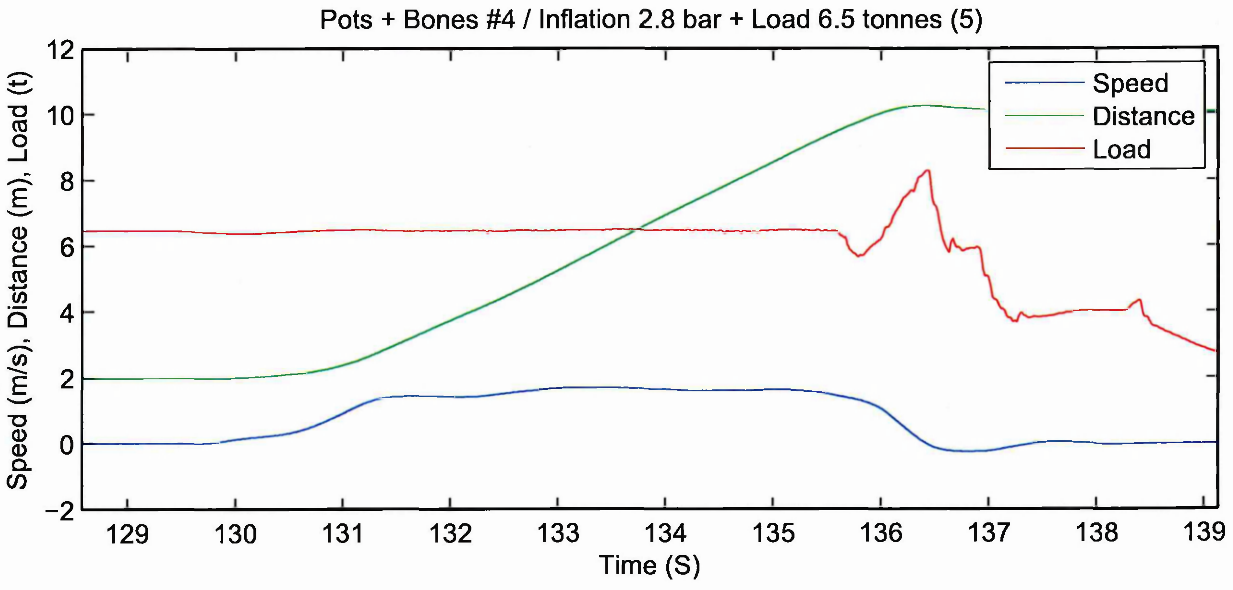

Pressure (Bar)
first
second
third
fourth
10
8
6
4
2
0
−2
176
178
180
182
184
186
188
190

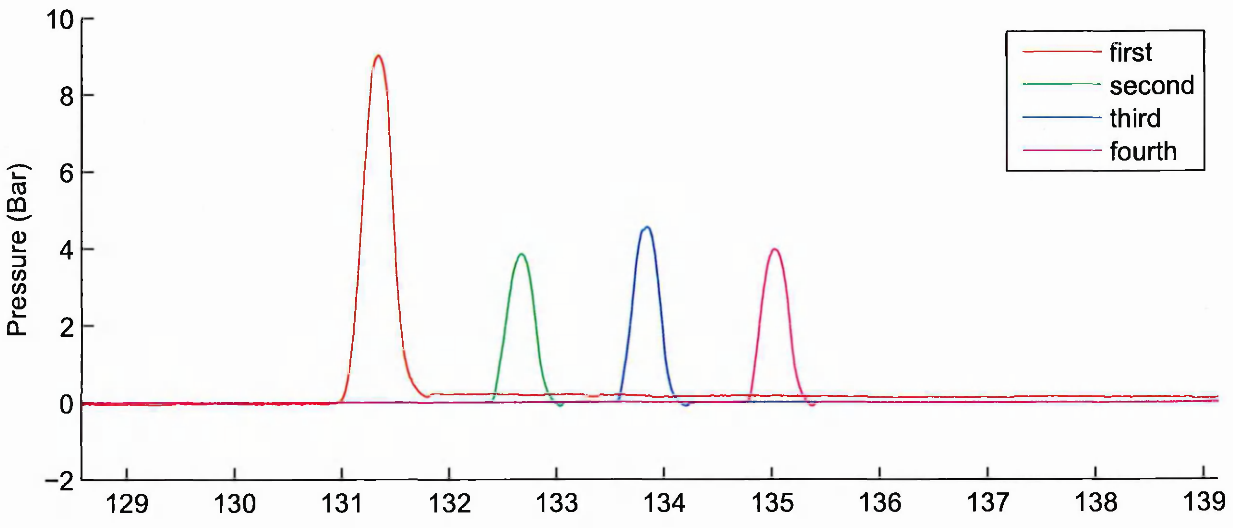

Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
10
8
6
4
2
0
176
178
180
182
184
186
188
190

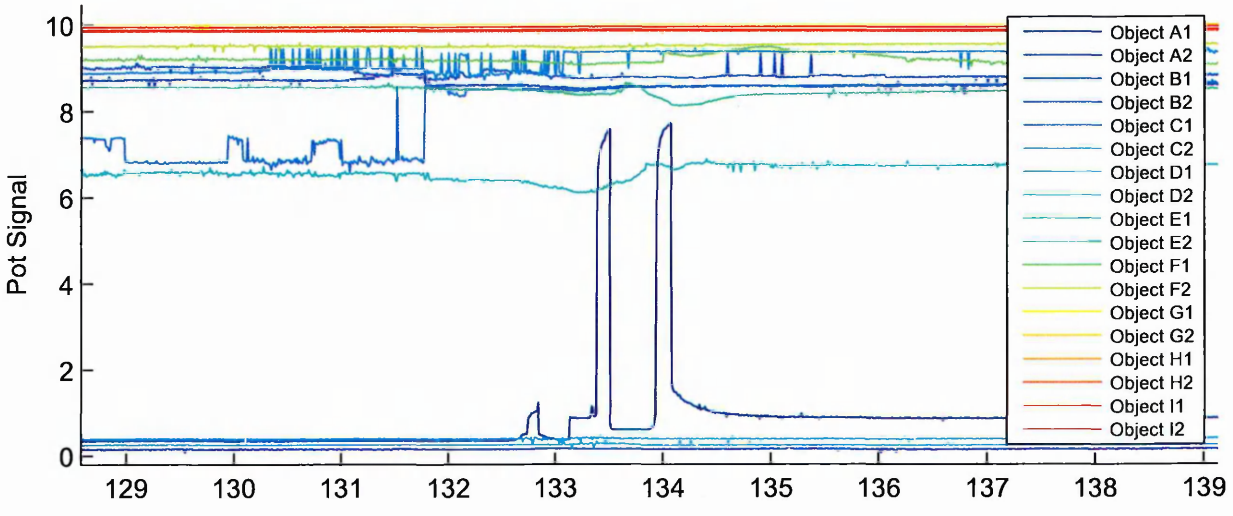

Pots + Bones #4 / Inflation 2.8 bar + Load 6.5 tonnes (4)
Speed
Distance
Load
Speed (m/s), Distance (m), Load (t)
Time (S)
12
10
8
6
4
2
0
−2
110
112
114
116
118
120


first
second
third
fourth
Pressure (Bar)
10
8
6
4
2
0
−2
110
112
114
116
118
120

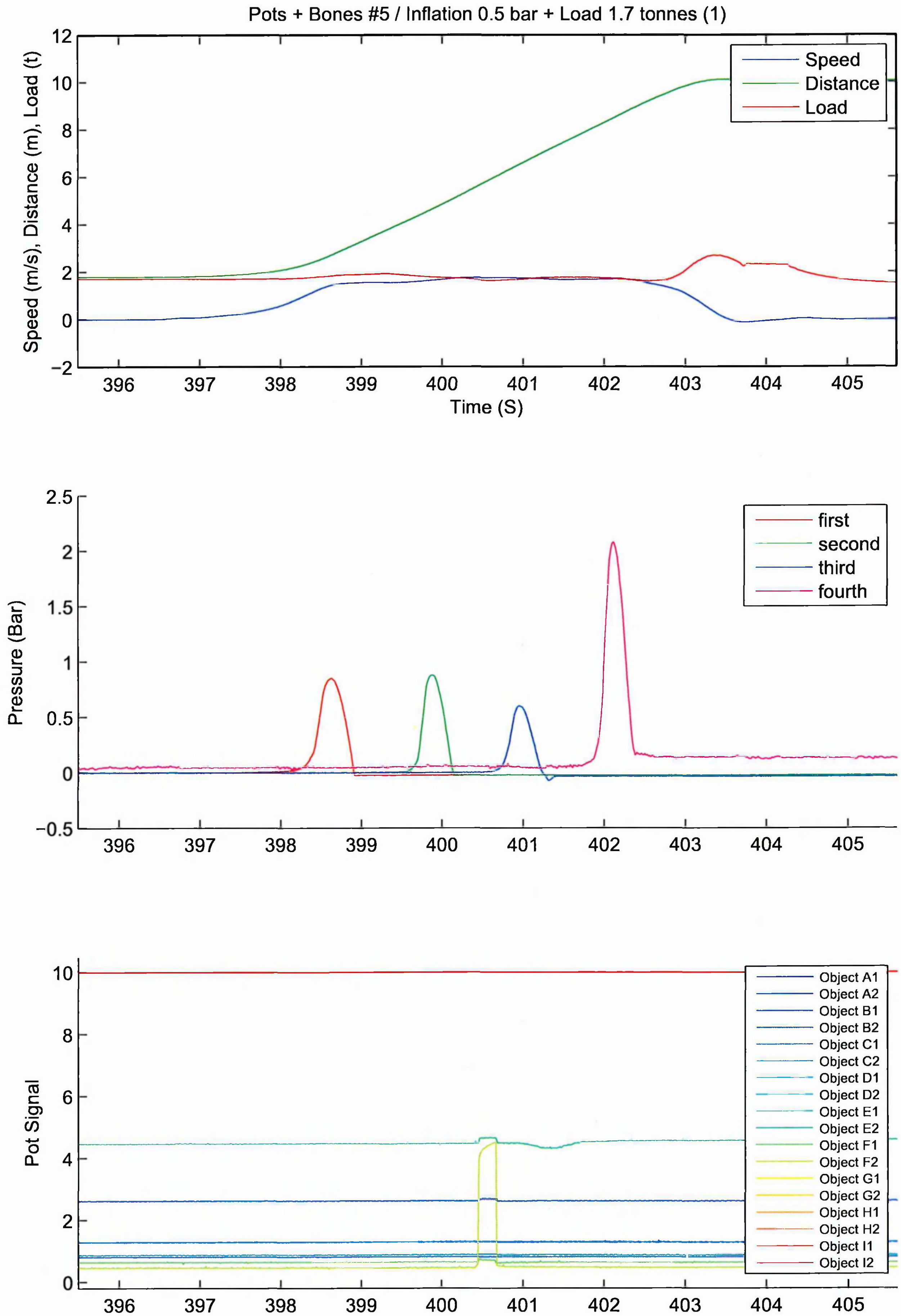

Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
Pot Signal
10
8
6
4
2
0
110
112
114
116
118
120

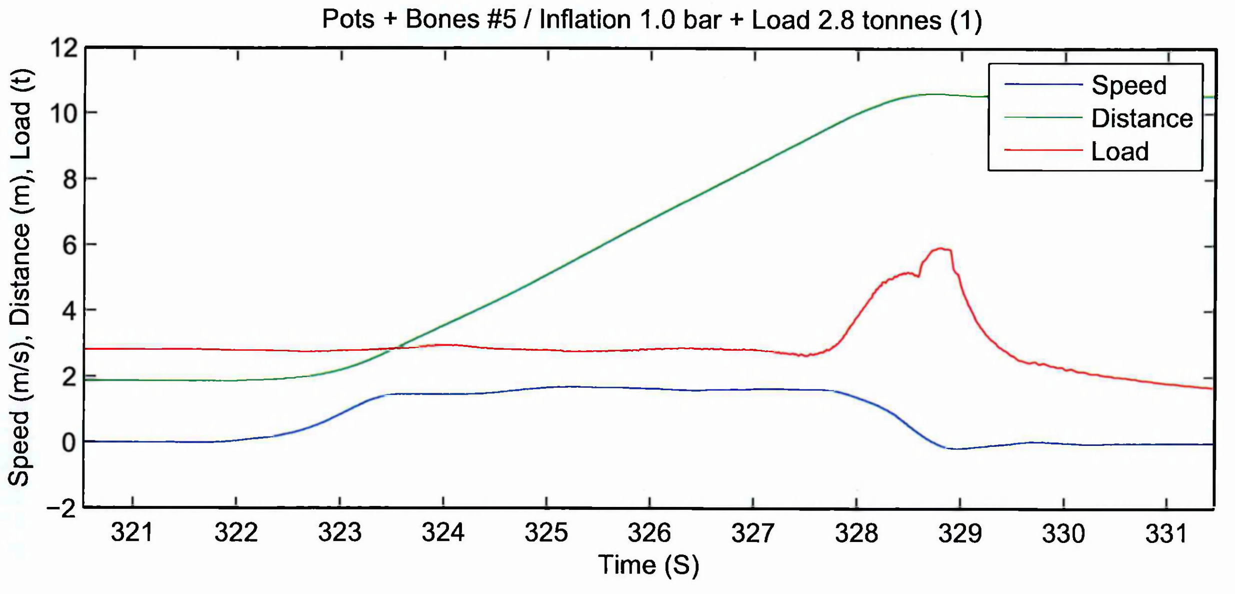

Pots + Bones #4 / Inflation 2.8 bar + Load 6.5 tonnes (5)
Speed (m/s), Distance (m), Load (t)
Time (S)
Speed
Distance
Load


Pressure (Bar)
first
second
third
fourth

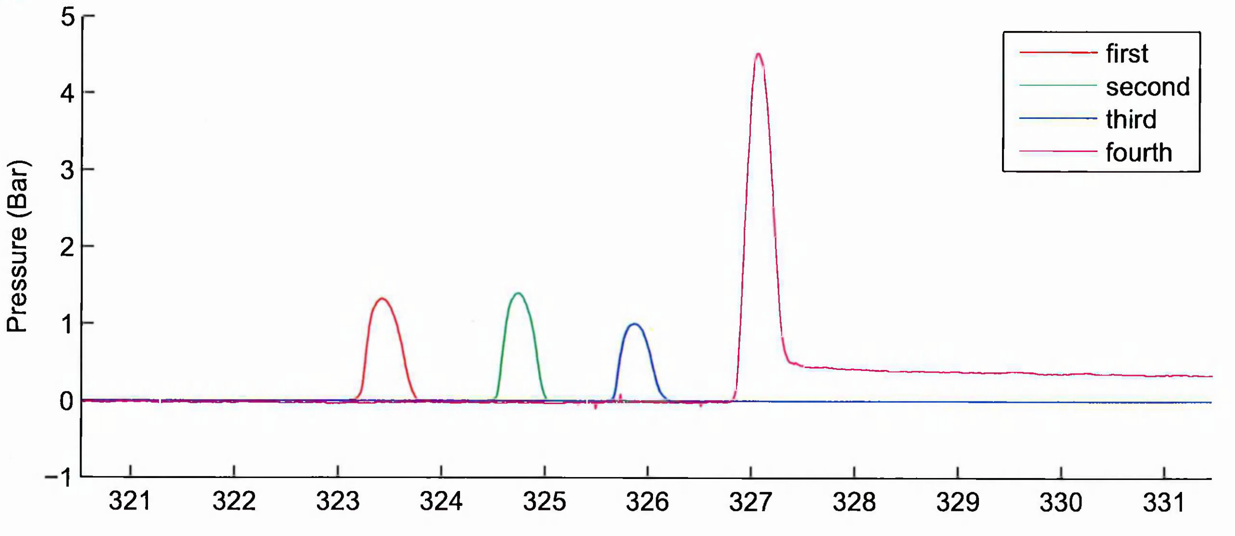

Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2

R5	R5
Object A1	X
Object A2	X
Object B1	roman thrown rim
Object B2	roman thrown body
Object C1	sand + flint tempered rim
Object C2	sand + flint tempered body
Object D1	X
Object D2	X
Object E1	flint beaker rim
Object E2	flint beaker body
Object F1	shell tempered body
Object F2	shell tempered rim
Object G1	X
Object G2	X
Object H1	X
Object H2	X
Object I1	X
Object I2	X

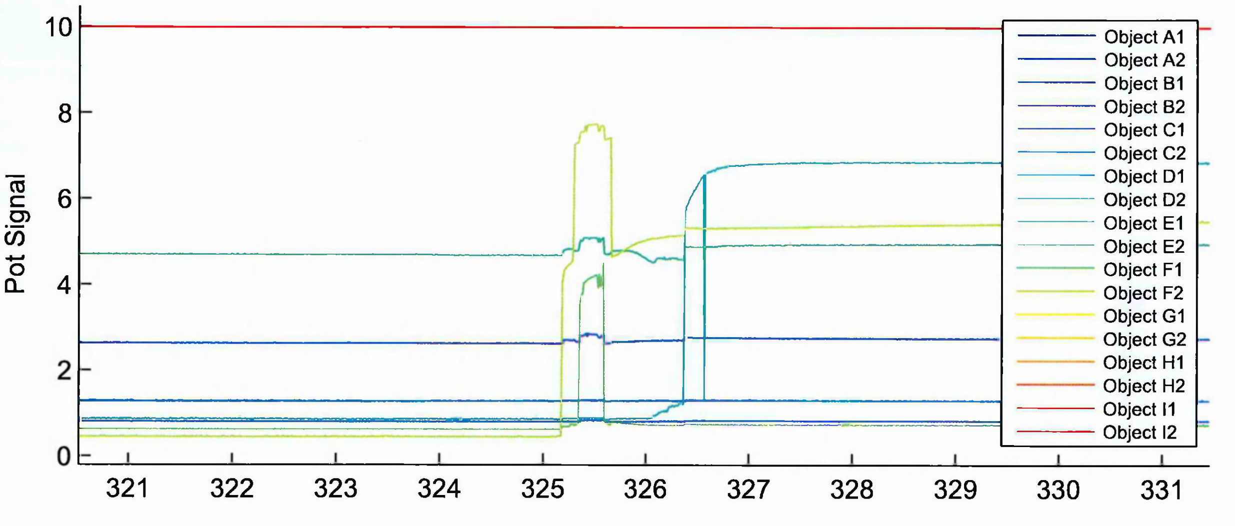

Pots + Bones #5 / Inflation 0.5 bar + Load 1.7 tonnes (1)
Speed (m/s), Distance (m), Load (t)
Speed
Distance
Load
Time (S)
Pressure (Bar)
first
second
third
fourth
Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2



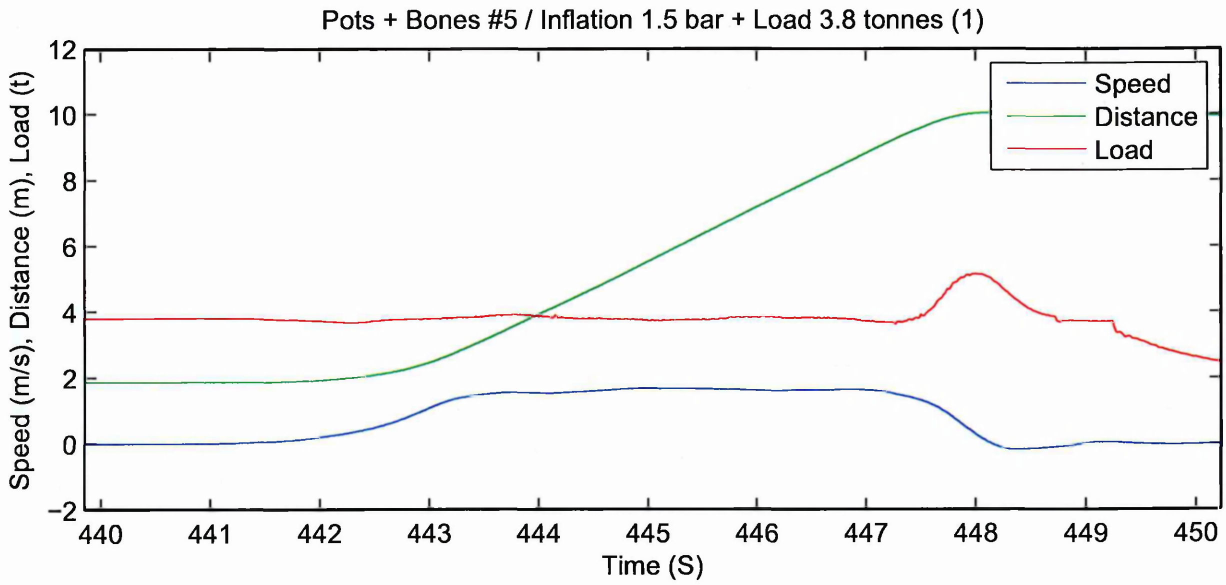
Pots + Bones #5 / Inflation 1.0 bar + Load 2.8 tonnes (1)
Speed
Distance
Load
Speed (m/s), Distance (m), Load (t)
Time (S)



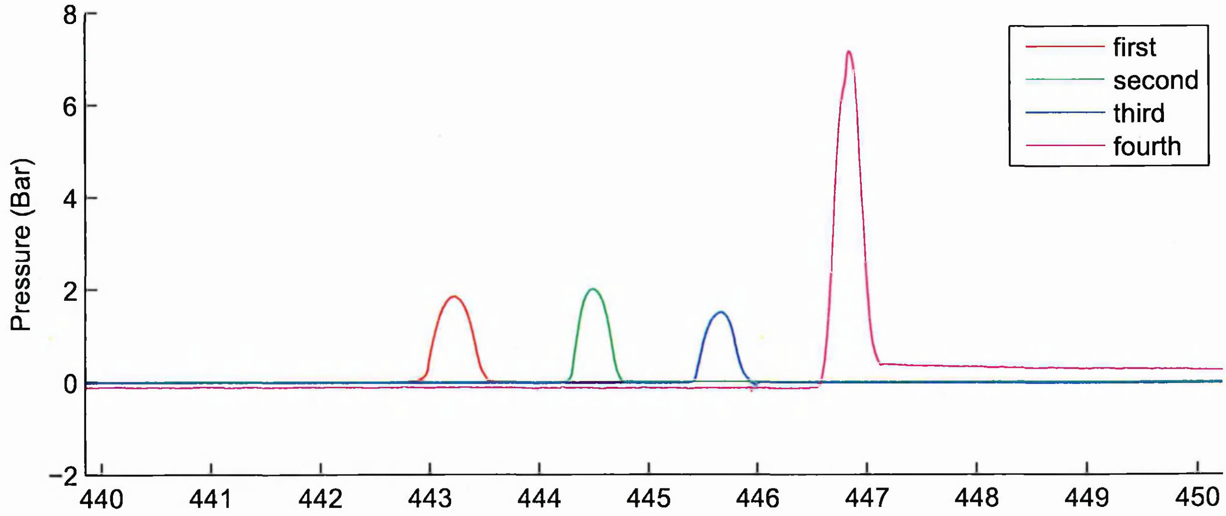
first
second
third
fourth
Pressure (Bar)



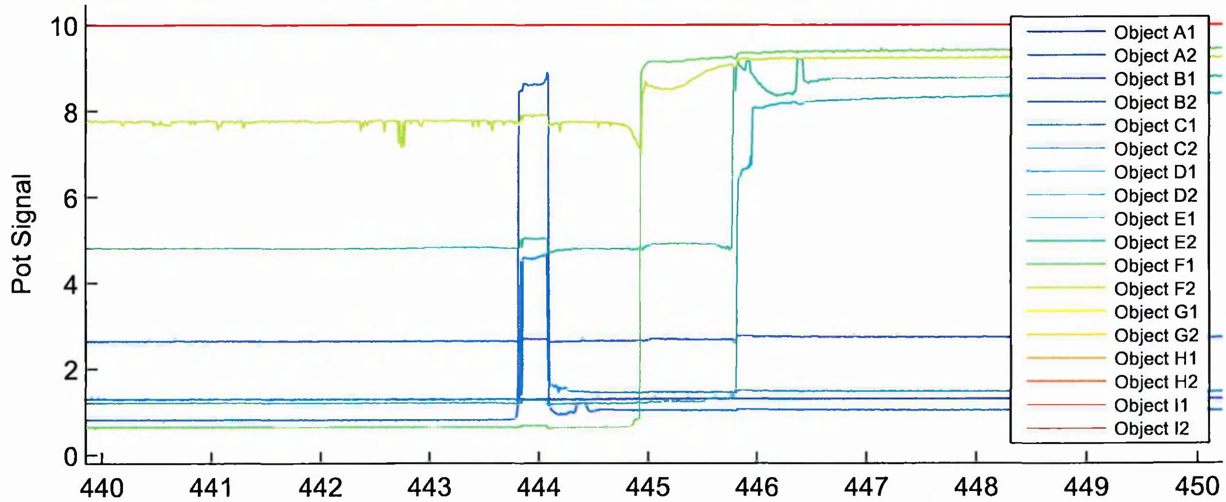
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
Pot Signal



Pots + Bones #5 / Inflation 1.5 bar + Load 3.8 tonnes (1)
Speed
Distance
Load
Speed (m/s), Distance (m), Load (t)
Time (S)
12
10
8
6
4
2
0
-2
440
441
442
443
444
445
446
447
448
449
450

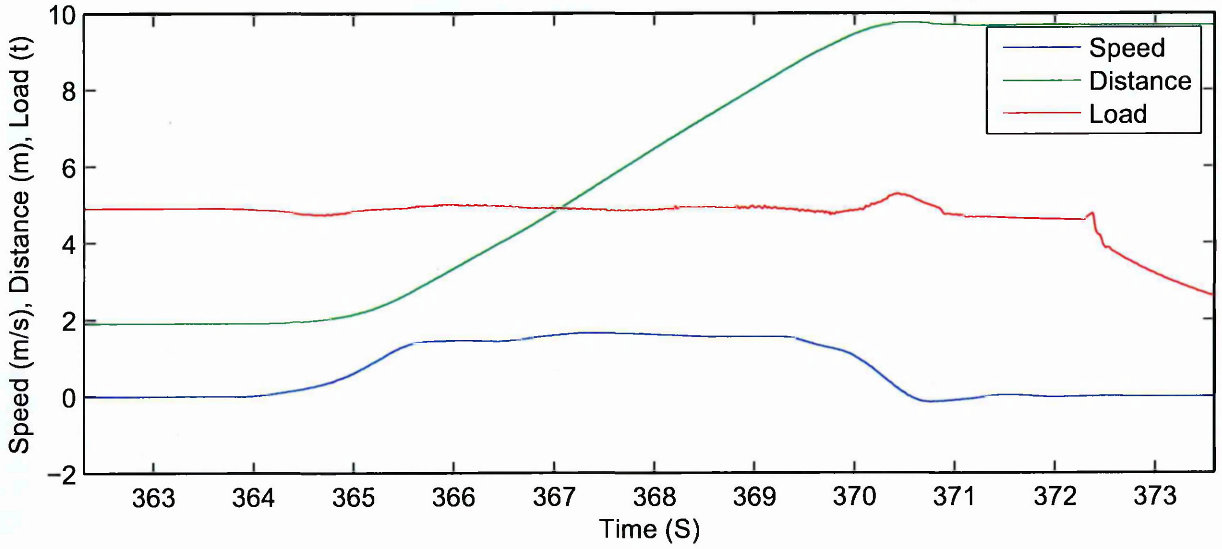


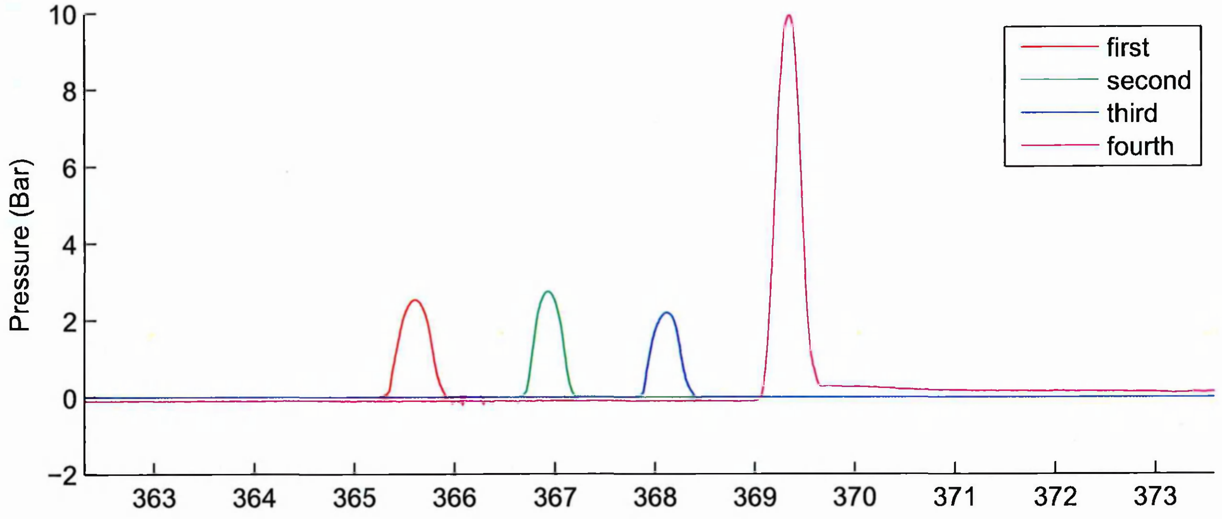
first
second
third
fourth
Pressure (Bar)
8
6
4
2
0
-2
440
441
442
443
444
445
446
447
448
449
450

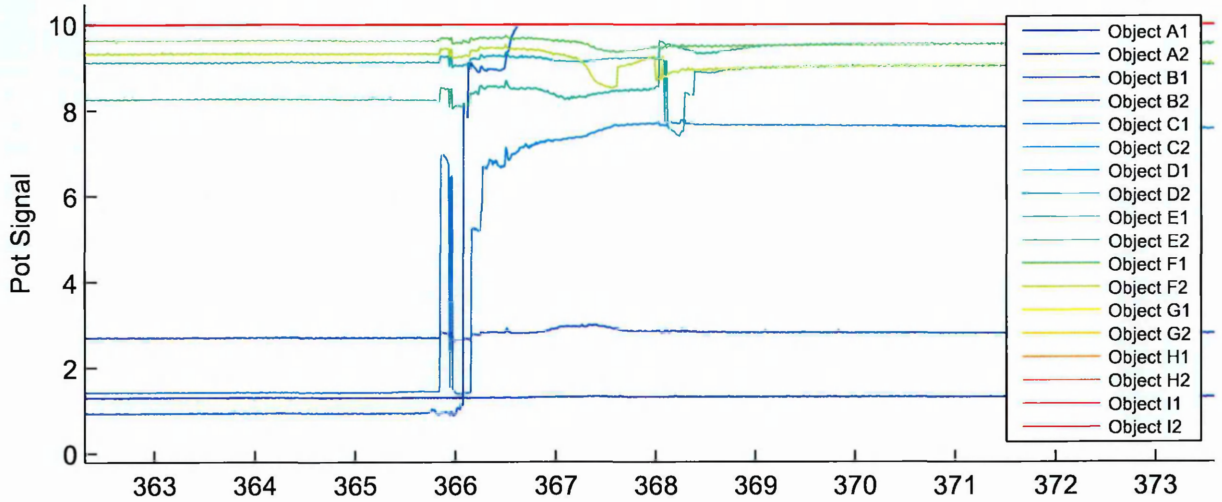


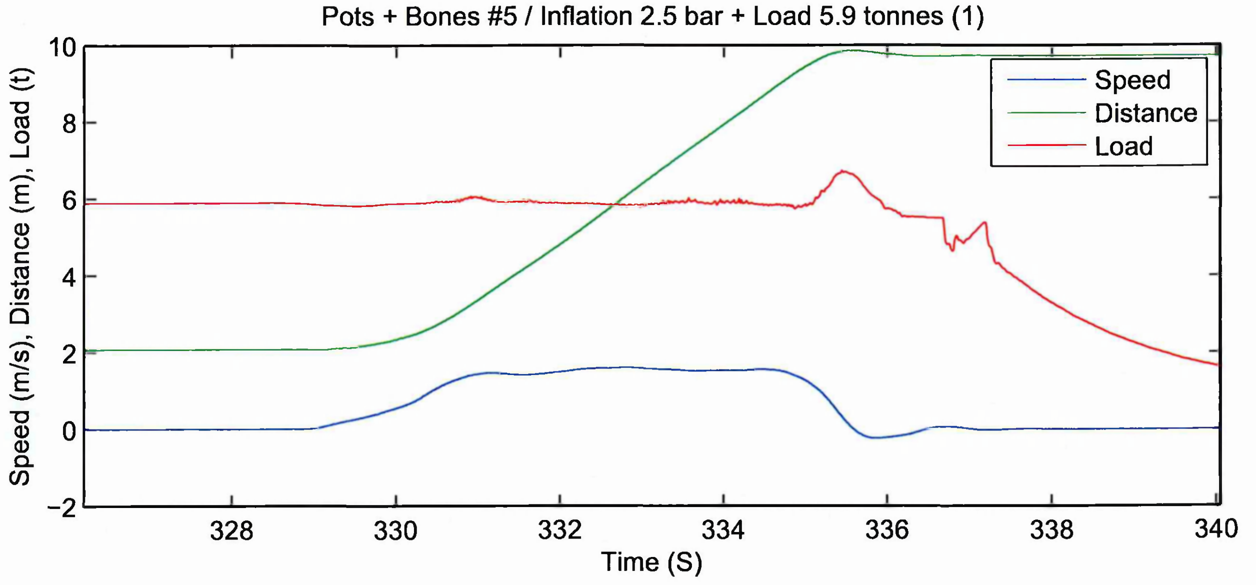
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
Pot Signal
10
8
6
4
2
0
440
441
442
443
444
445
446
447
448
449
450

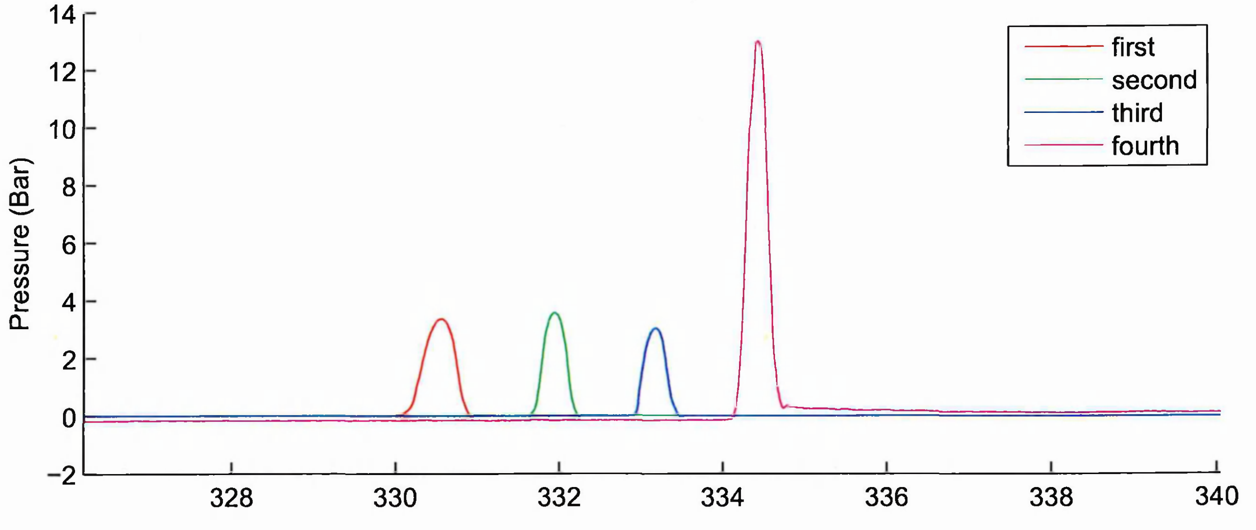
Pots + Bones #5 / Inflation 2.0 bar + Load 4.9 tonnes (1)

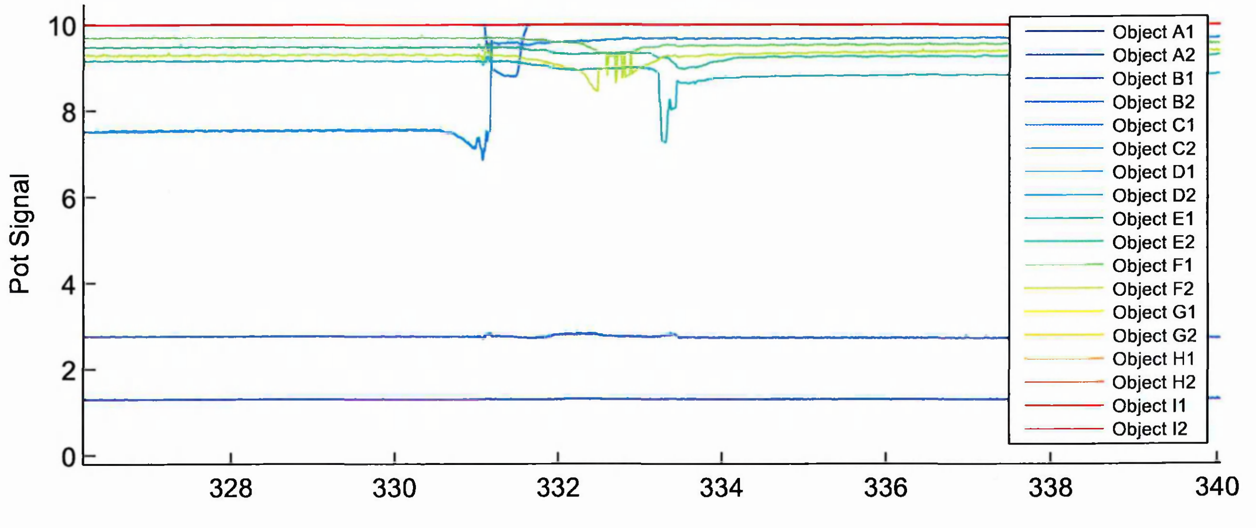


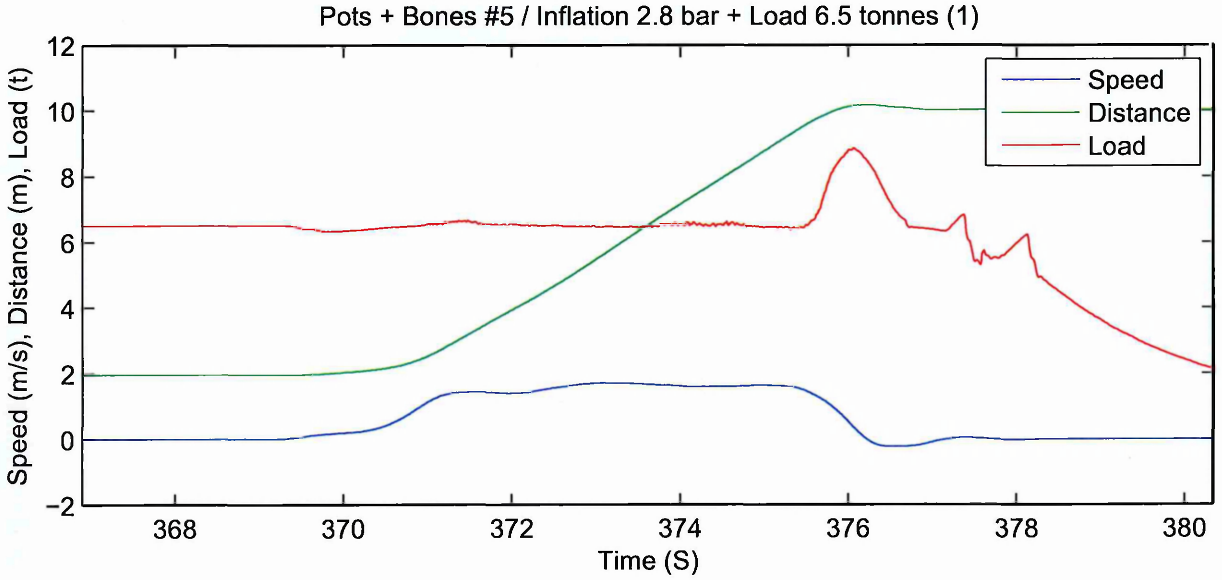




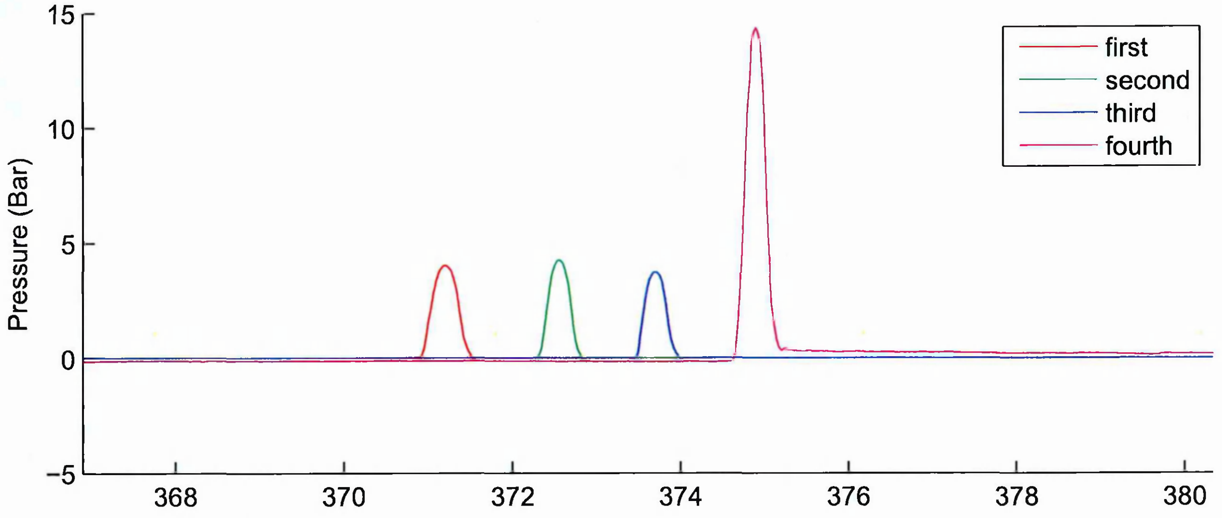

Pots + Bones #5 / Inflation 2.5 bar + Load 5.9 tonnes (1)
Speed
Distance
Load
Speed (m/s), Distance (m), Load (t)
Time (S)
10
8
6
4
2
0
-2
328
330
332
334
336
338
340


first
second
third
fourth
Pressure (Bar)
14
12
10
8
6
4
2
0
-2
328
330
332
334
336
338
340

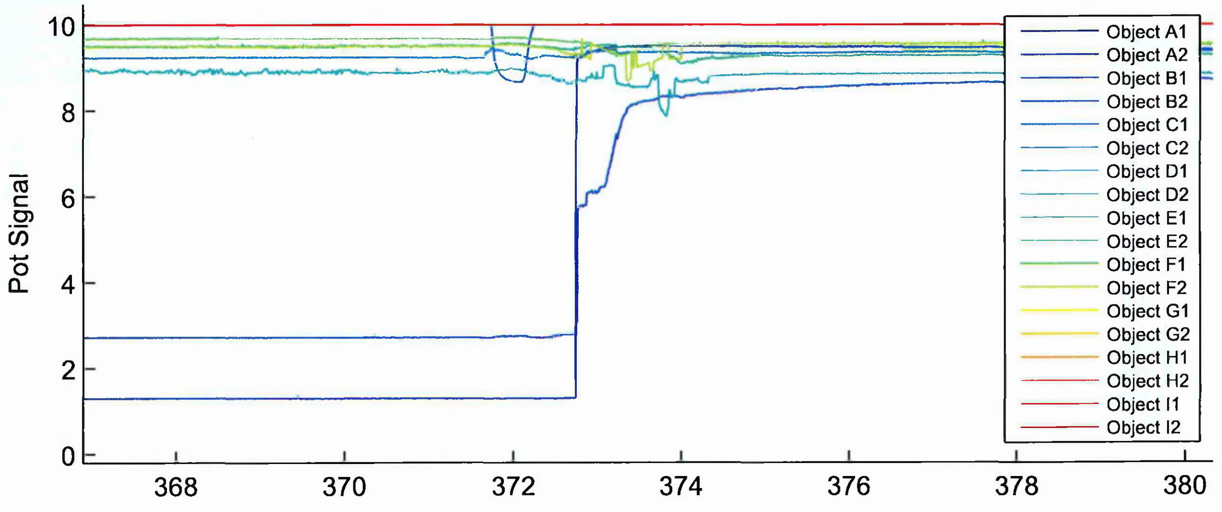

Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
Pot Signal
10
8
6
4
2
0
328
330
332
334
336
338
340



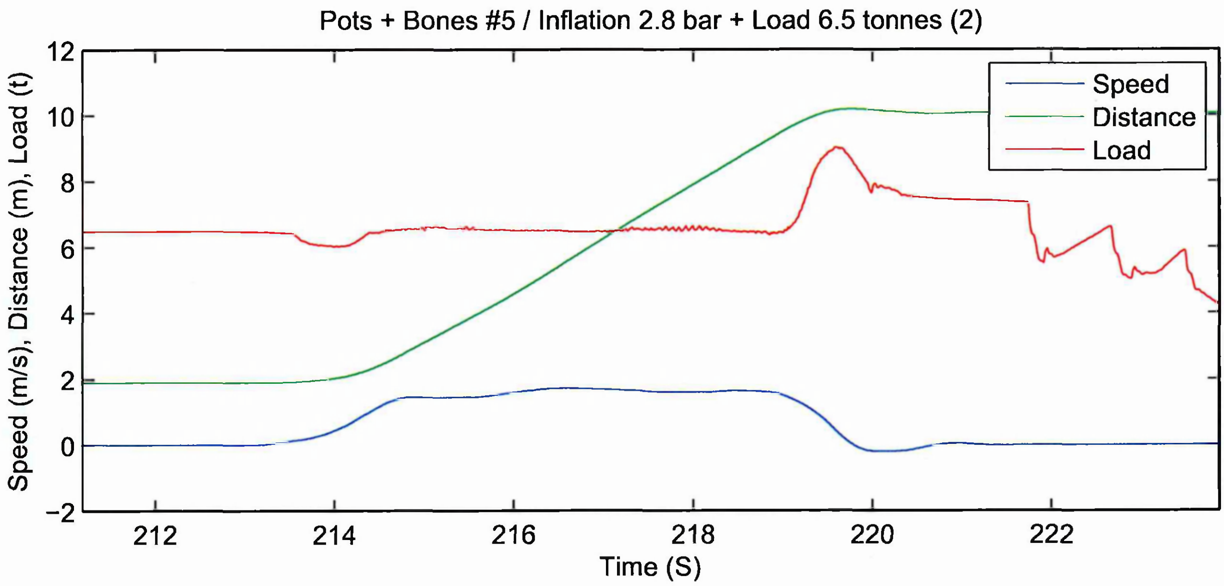
Pots + Bones #5 / Inflation 2.8 bar + Load 6.5 tonnes (1)
Speed (m/s), Distance (m), Load (t)
12
10
8
6
4
2
0
-2
368
370
372
374
376
378
380
Time (S)
Speed
Distance
Load

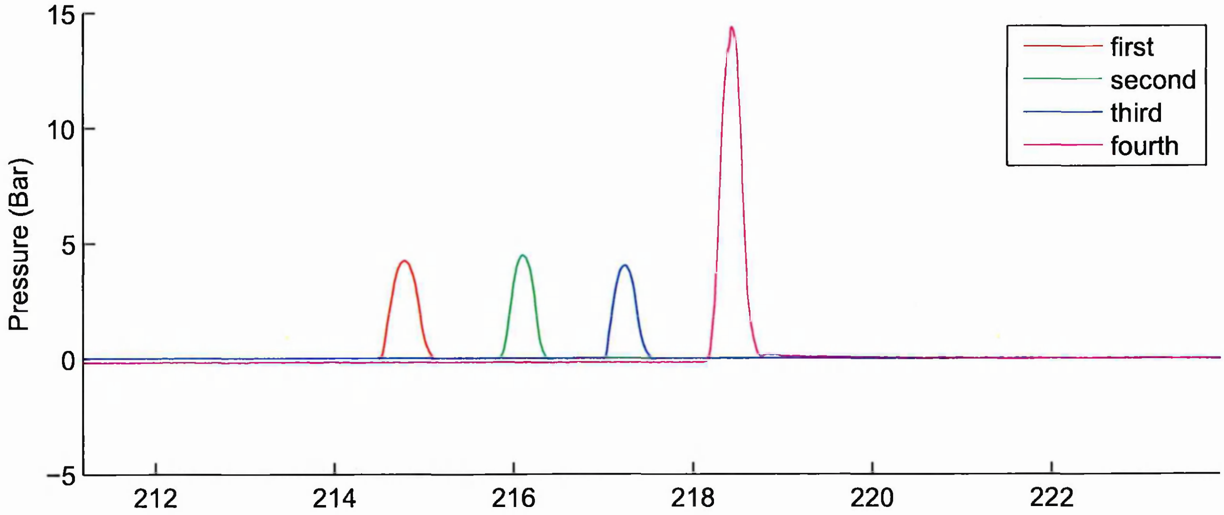


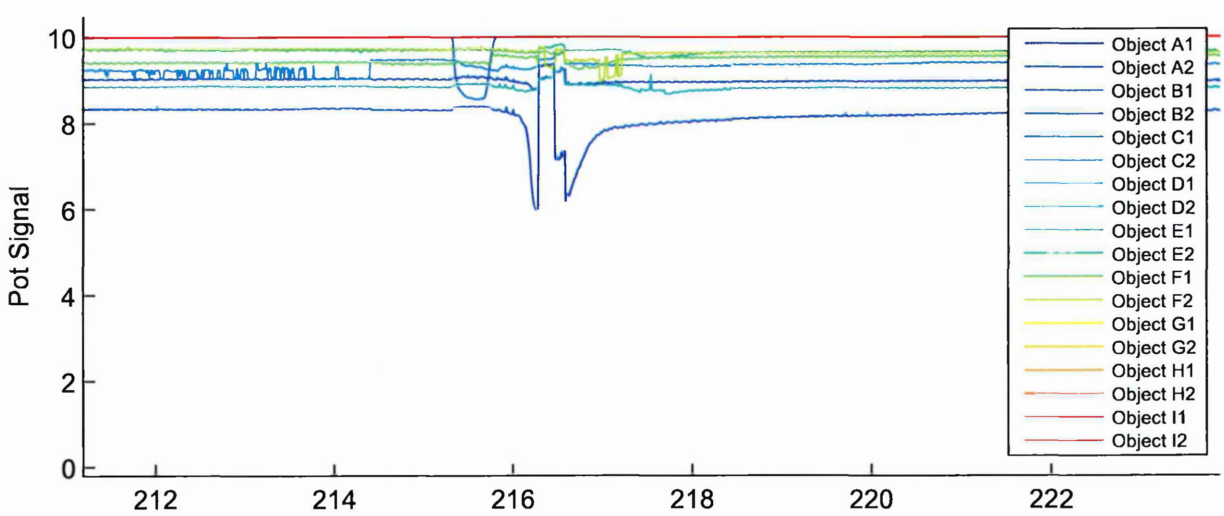
Pressure (Bar)
15
10
5
0
-5
368
370
372
374
376
378
380
first
second
third
fourth

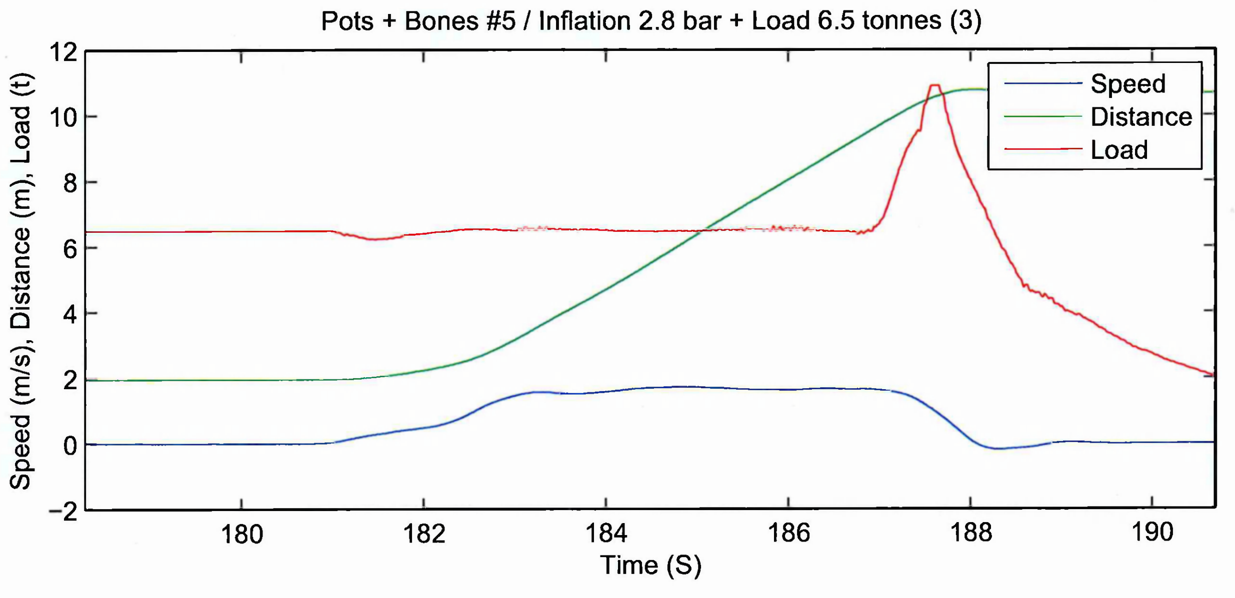


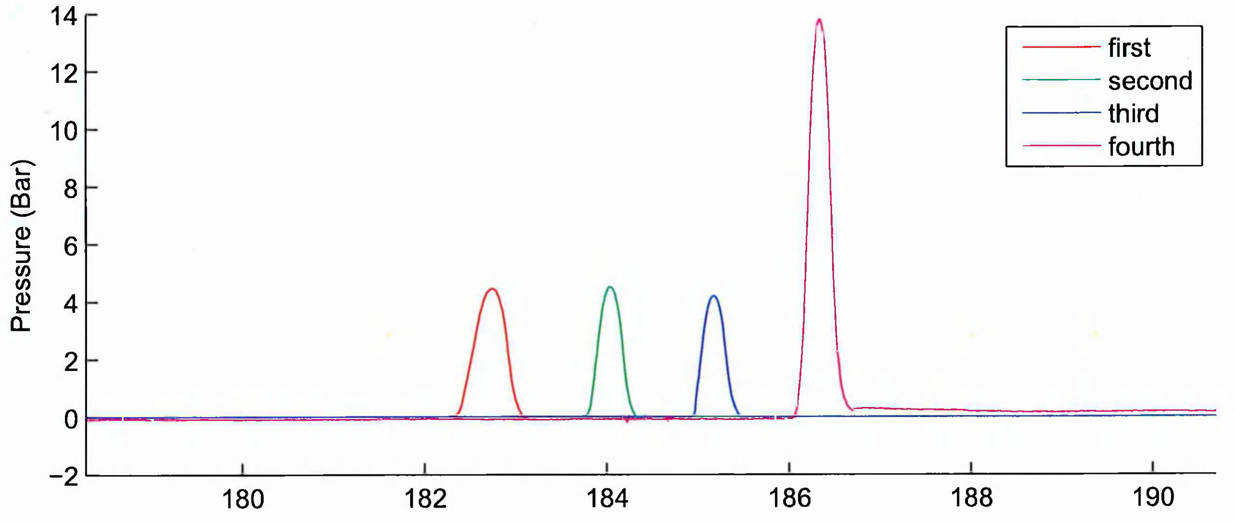
Pot Signal
10
8
6
4
2
0
368
370
372
374
376
378
380
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2

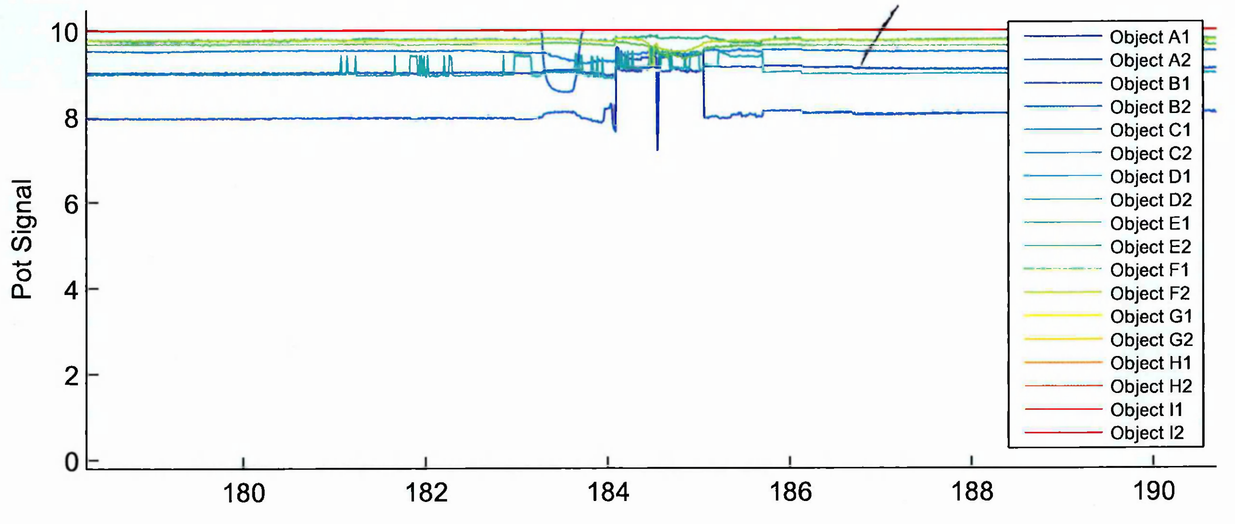

Pots + Bones #5 / Inflation 2.8 bar + Load 6.5 tonnes (2)
Speed (m/s), Distance (m), Load (t)
Time (S)
Speed
Distance
Load
12
10
8
6
4
2
0
−2
212
214
216
218
220
222

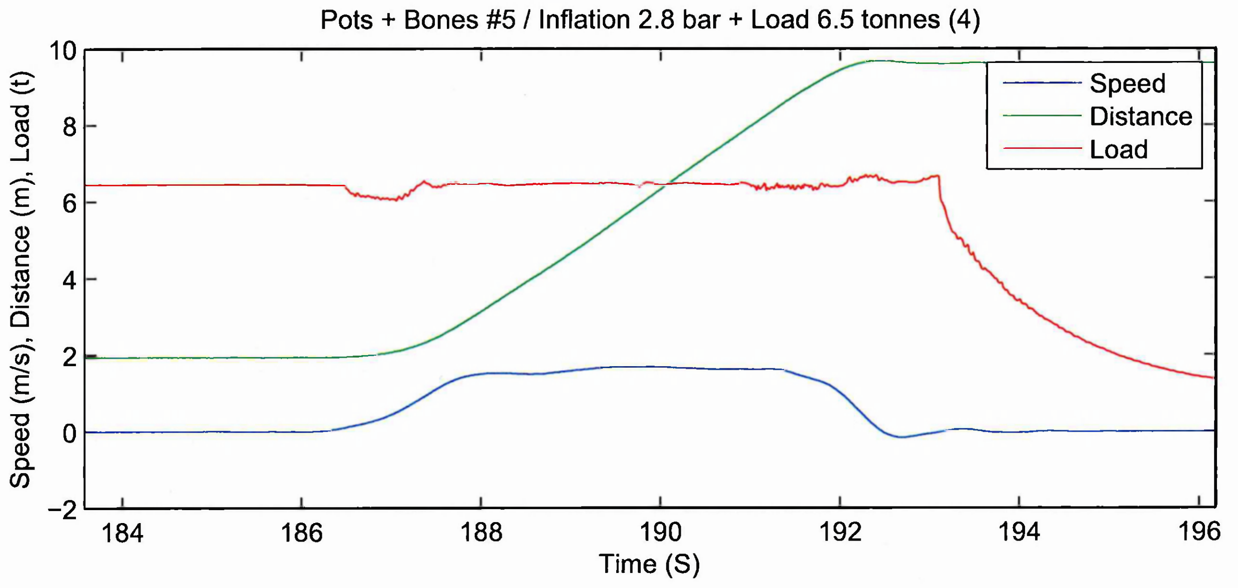

Pressure (Bar)
first
second
third
fourth
15
10
5
0
−5
212
214
216
218
220
222

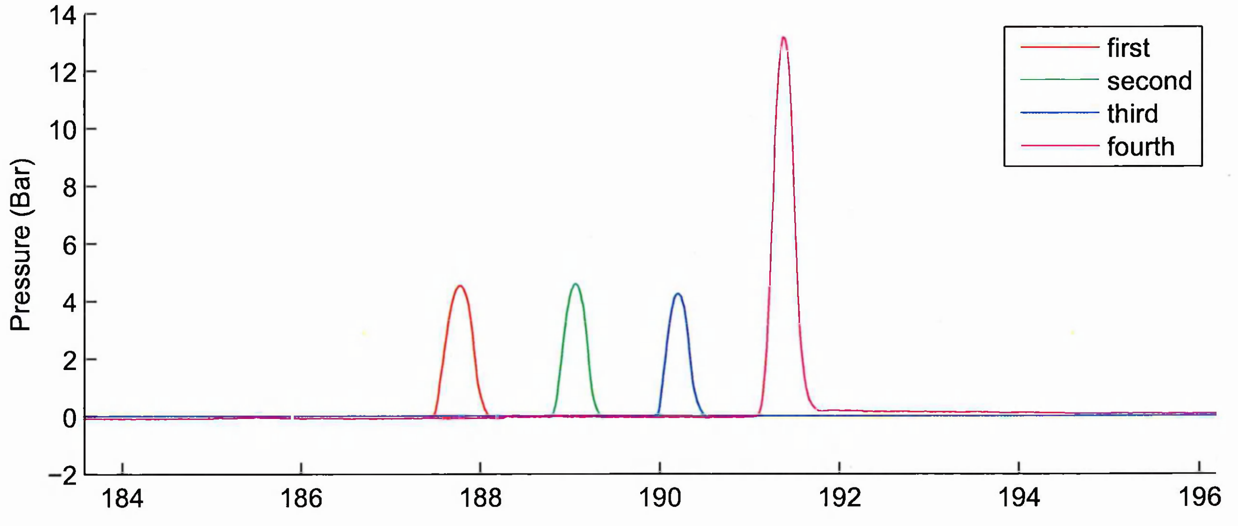

Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
10
8
6
4
2
0
212
214
216
218
220
222

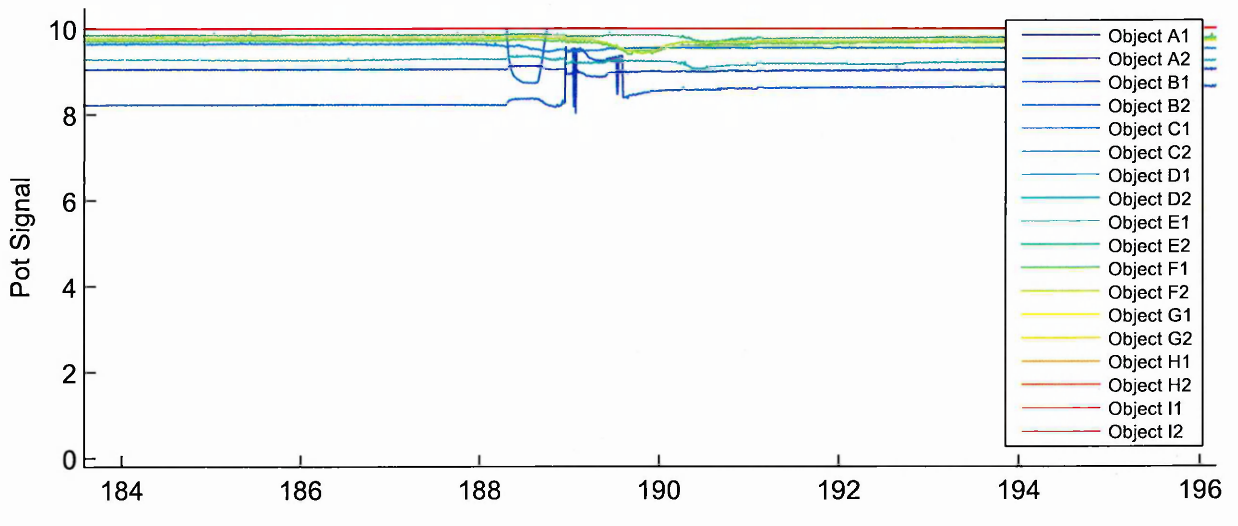

Pots + Bones #5 / Inflation 2.8 bar + Load 6.5 tonnes (3)
Speed
Distance
Load
Speed (m/s), Distance (m), Load (t)
Time (S)
12
10
8
6
4
2
0
-2
180
182
184
186
188
190


first
second
third
fourth
Pressure (Bar)
14
12
10
8
6
4
2
0
-2
180
182
184
186
188
190


Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
Pot Signal
10
8
6
4
2
0
180
182
184
186
188
190


Pots + Bones #5 / Inflation 2.8 bar + Load 6.5 tonnes (4)
Speed (m/s), Distance (m), Load (t)
Time (S)
Speed
Distance
Load
10
8
6
4
2
0
−2
184
186
188
190
192
194
196


Pressure (Bar)
first
second
third
fourth
14
12
10
8
6
4
2
0
−2
184
186
188
190
192
194
196


Pot Signal
Object A1
Object A2
Object B1
Object B2
Object C1
Object C2
Object D1
Object D2
Object E1
Object E2
Object F1
Object F2
Object G1
Object G2
Object H1
Object H2
Object I1
Object I2
10
8
6
4
2
0
184
186
188
190
192
194
196

Appendix L: Human Bone data

This appendix includes the information on the physical properties of the aged, non-stratified human radius bones used within this research.

All measurements are in millimetres (mm)

Trial #1:

Perpendicular-orientated bone:

Total length = 222 mm

Lengths of broken pieces after testing:
L_1 = 99 mm
L_2 = 123 mm

Dimensions at breakage point:
Height = 13 mm
Width = 18 mm

Dimensions of end of bone:
Distal = 23 mm diameter
Proximal = 32 mm x 20 mm (estimating a rectangle)

Cortical thickness of bone at break point was between 2 and 4 mm thickness.

Parallel-orientated bone:

Total length = 225 mm

Dimensions at centre of bone:
Height = 10 mm
Width = 15 mm

Dimensions of end of bone:
Distal = 20 mm diameter
Proximal = 21 mm x 33 mm (estimating a rectangle)

Cortical thickness of bone unknown as it did not break

Trial #2:

Perpendicular-orientated bone:

Total length = 206 mm

Lengths of broken pieces after testing:
L_1 = 90 mm

L_2 = 116 mm

Dimensions at breakage point:
Height = 10 mm
Width = 16 mm

Dimensions of end of bone:
Distal = 18 mm diameter
Proximal = 18 mm x 22 mm (estimating a rectangle)

Cortical thickness of bone at break point was between 4 and 9 mm thickness.

Parallel-orientated bone:

Total length = 216 mm

Dimensions at centre of bone:
Height = 12 mm
Width = 17 mm

Dimensions of end of bone:
Distal = 21 mm diameter
Proximal = 21 mm x 31 mm (estimating a rectangle)

Cortical thickness of bone unknown as it did not break

Trial #3:

Perpendicular-orientated bone:

Total length = 230 mm

Lengths of broken pieces after testing:
L_1 = 81 mm
L_2 = 149 mm

Dimensions at breakage point:
Height = 11 mm
Width = 16.5 mm

Dimensions at centre of bone length:
Height = 13 mm
Width = 17 mm

Dimensions of end of bone:
Distal = 20 mm diameter
Proximal = 24 mm x 33 mm (estimating a rectangle)

Cortical thickness of bone unknown as breakage was not complete. Crack depth was 8 mm.

Parallel-orientated bone:

Total length = 226 mm

Dimensions at centre of bone:
Height = 12 mm
Width = 15 mm

Dimensions of end of bone:
Distal = 23 mm diameter
Proximal = 25 mm x 33 mm (estimating a rectangle)

Cortical thickness of bone unknown as it did not break

Trial #4:

Perpendicular-orientated bone:

Total length = 230 mm

Dimensions at centre of bone length:
Height = 11 mm
Width = 15 mm

Dimensions of end of bone:
Distal = 20 mm diameter
Proximal = 22 mm x 31 mm (estimating a rectangle)

Cortical thickness of bone unknown as it did not break

Parallel-orientated bone:

Total length = 235 mm

Dimensions at centre of bone:
Height = 11 mm
Width = 17 mm

Dimensions of end of bone:
Distal = 20 mm diameter
Proximal = 23 mm x 32 mm (estimating a rectangle)

Cortical thickness of bone unknown as it did not break