

Numerical simulation of soil-cone penetrometer interaction using discrete element method

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Abstract

One of the most common methods to measure soil strength in-situ is cone penetrometers. In this paper the development of a three dimensional (3D) discrete element model (DEM) for the simulation of the soil-cone penetrometer interaction in a slightly cohesive loamy sand soil is presented. The aim was to investigate the effects of the soil model's geometrical (e.g., soil model cross section shape and size and model's height) changes on variations in the soil penetration resistance. The model area ratio and height ratio values were adopted to analyse the effects of the cross section size and the model's height, respectively. The results of penetration resistance of the DEM simulations were compared with the in-situ measurement with a cone penetrometer of the same geometry. This comparison allowed the derivation of the contact properties between the elements. To simulate the soil material the so-called Parallel Bond and Linear Models were used in the 3D version of the Particle Flow Code (PFC) software. Finally the mechanical properties of the soil, namely the cohesion and internal friction angle were estimated by DEM simulation of direct shear box.

Results showed that the penetration process can be simulated very well using the DEM. The model's calculated penetration resistance and the corresponding in-situ measurement were in good agreement, with mean error of 14.74 %. The best performing models were a rectangular model with an area ratio of 72 and a height ratio of 1.33 and a circular model with an area ratio of 32 and a height ratio of 2. The simulation output of soil material properties with direct shear box resulted in representative values of real loamy sand soils, with cohesion values range of 6.61-8.66 kPa and internal friction angle values range of 41.34-41.60°. It can be concluded that the DEM can

43 be successfully used to simulate the interaction between soil
44 and cone penetrometers in agricultural soils.

45 Keywords: Discrete element method, cone penetrometer, soil
46 mechanics.

47 **1. Introduction**

48 Soil compaction is the most known natural and manmade
49 problem that negatively affects crop growth and yield, reduces
50 soil hydraulic properties and increases soil susceptibility to
51 erosion (Hamza and Anderson, 2005; Fleige and Horn, 2000).
52 It directly results in increasing the cost of agriculture
53 production due to the need for tillage operations (Garner et al.,
54 1987; Mouazen and Ramon, 2002), which is a highly
55 consuming energy operation. With the increase in agriculture
56 machine size, machine mass tends to increase dramatically in
57 the last few decades, which resulted in increasing the amount of
58 normal stress applied into agriculture soils by both the driving
59 and non-driving wheels and tracks. However, the traction
60 produced under the driving wheels also leads to the generation
61 of shear stress. Both the normal and shear stresses augment soil
62 strength and as a result soil compaction is increased. One of the
63 most common methods to measure soil strength is cone
64 penetrometers.

65 Cone penetrometers are commonly used to measure the
66 penetration resistance at a certain speed (McKyes, 1985),
67 throughout the soil profile. The output of the measurement is
68 the cone index (C. I.), which can be determined by dividing the
69 penetration force to the cone projected area. The cone index
70 depends on the soil properties, namely the water content, bulk
71 density and particle size distribution (Sudduth et al., 2008). A
72 second main reason to use cone penetrometers in the field is
73 that they measure the bearing capacity of the soil, which is
74 important not only in civil engineering projects but in
75 agriculture too. Since penetrometers have small projected area
76 of 1-2 cm², they demand smaller penetration forces that can be
77 provided by an operator (Laib, 2002). However, during field
78 measurement penetrometers readings show high standard
79 deviation, which is normally attributed to the heterogeneity of
80 the soil, e.g., presence of stones or holes with the same
81 dimension or bigger than the cone projected area (Sudduth
82 et al., 2008; Fountas et al., 2013). This disadvantage can be
83 compensated by performing high number of penetration tests
84 on the same spot in the field (Laib, 2002), after which an
85 average value can be calculated. However, performing multiple
86 measurements on the same spot is a time consuming and costly

87 operation. Therefore, efforts have been made to automatically
88 measure penetration resistance, by utilising the tractor's three
89 point linkage and hydraulic power. Multiple penetrometers
90 were designed and combined with GPS receivers to obtain
91 multiple measurements at the same time (Fountas et al., 2013).

92 Numerical simulation methods e.g., the finite element method
93 (FEM) and discrete element method (DEM) are good
94 alternative approaches to substitute the in-situ tedious, costly
95 and time consuming experimental work. With the recent
96 evolution of the information technology numerical simulations,
97 particularly for soil-tillage and soil-wheel interaction become
98 more popular (Mouazen and Neményi, 1998). The most
99 common simulation methods used so far are FEM (Chi and
100 Kushwaha, 1990; Kerényi, 1996; Mouazen and Neményi, 1999;
101 Bentaher et al., 2013; Fervers, 2004), DEM (Shmulevich et al.,
102 2007; Knuth et al., 2012; Tamás et al., 2013) and computational
103 fluid dynamics (CFD) (Formato et al., 2005). The FEM has
104 been used to simulate both homogenous (e.g. Chi and
105 Kushwaha, 1990) and non-homogeneous (e.g. Mouazen and
106 Neményi, 1998) soil material, modelled as a continuum. Less
107 effort was reported on the simulation of soil penetration
108 (Tekeste et al., 2007; Foster Jr. et al., 2005). Since soil consists
109 of individual particles of different size, the simulation is more
110 appropriate to be done with the DEM, established by Cundall
111 and Strack (1979). This method can be used to simulate
112 granular assemblies because the material is modelled as a group
113 of individual elements with their contacts. DEM has been used
114 in several agricultural fields, e.g. to model the interaction
115 between soil and tillage tools (e.g., Tamás et al., 2013; Chen
116 et al., 2013), and to simulate the material overflow and the
117 discharging process from silos (e.g., Keppler et al., 2012; Goda
118 and Ebert, 2005). There are also several published works about
119 the simulation of the soil-wheel interaction using the DEM
120 (Smith and Peng, 2013; Khot et al., 2007). Many research
121 works were published about the use of the DEM to study the
122 dynamic motion of the Mars rover's or the lunar rover's wheel
123 (Knuth et al., 2012; Nakashima et al., 2010). To our best
124 knowledge only limited research on the simulation of the soil-
125 cone penetrometer was reported in the literature, particularly in
126 agricultural soils. Wang and Zhao (2014) and Tanaka et al.
127 (2000) used the DEM to simulate this phenomenon in two
128 dimension (2D) and Butlanska et. al. (2014) and Lin and Wu
129 (2012) in three dimension (3D) but only for non-cohesive soils.
130 Arroyo et. al (2009) investigated the effects of homogeneity
131 and symmetry of the discrete element model on cone
132 penetration and experienced differences in the soil resistance

133 between, the half, quarter and full size model. Furthermore,
 134 large portion of error in DEM simulations is attributed to the
 135 difficulties associated with the determination of contacts
 136 properties between soil particles at micro scale correctly, which
 137 necessitates further research to accurately determine these
 138 contact properties.

139 This paper aims at the development of a 3D DEM model for the
 140 simulation of the soil penetration with a cone penetrometer in a
 141 slightly cohesive loamy sand soil. It will aim at the
 142 optimisation of the dimensions of the soil model (shape and
 143 size of the cross section and model height) for accurate
 144 prediction of penetration resistance.

145 **2. Development of the discrete element model**

146 *2.1. In-situ tests*

147 In-situ tests for the measurement of penetration resistance were
 148 performed at the experimental farm of Szent István University
 149 of Gödöllő (Máthé et al., 2013, Máthé, 2014), using a standard
 150 Eijkelkamp penetrometer (Eijkelkamp, Netherland) in the
 151 track of the GAZ-69 (69A) type of vehicle.

152 The cone's bevel angle was 60° and its projected area was
 153 0.0002 m^2 (see Fig. 1). Two measurement series with 10
 154 repetitions each were performed, namely one series in front of
 155 the left wheel and one in front of the right wheel of the vehicle
 156 pushing the penetrometer with velocity of 0.01 m s^{-1} into the
 157 soil. The 10 measurement of each series were averaged in one
 158 value. According to the results of the measurements the soil
 159 penetration resistance has high standard deviation of 0.48 MPa,
 160 0.55 MPa and 0.52 MPa at depth of 0.05 m, 0.1 m and 0.15 m,
 161 respectively, which can be experienced in real soils (Laib,
 162 2002; Sudduth et al., 2008; Fountas et al., 2013). During
 163 penetration resistance measurement, soil samples were
 164 collected with core cylinders to determine the average bulk
 165 density, moisture content and porosity (Table 1).

166 Table 1. The measured soil properties at the time of penetration resistance
 167 measurement (Máthé et al., 2013, Máthé, 2014).

Parameter	Value
Soil type (-)	Loamy sand with 90,5% sand, 3,2% silt and 6,3% clay
Bulk density (kg m^{-3})	1632
Moisture content (% dry basis)	15.8
Porosity (-)	0.36

168 *2.2. Construction of discrete element model*

169 The simulation of soil penetration with the same cone
 170 penetrometer of Eijkelkamp penetrometer (Eijkelkamp,
 171 Netherlands) was carried out using the Particle Flow Code
 172 software (PFC3D ITASCATM, USA). In the PFC3D software
 173 the material can be modelled using only rigid ball elements.
 174 Each particle can be in contact with the adjacent balls and
 175 walls. If a contact exists between two elements (ball and ball or
 176 ball and wall) the contact force can be calculated from the
 177 stiffness and the relative position of the contacting elements
 178 (Potyondy and Cundall, 2004). Afterwards, the displacement of
 179 each element is determined according to the Newton's second
 180 law, expressed by the following two vector equations (Itasca,
 181 1999):

$$182 \quad F_i = m \cdot (\ddot{x}_i - g_i) \quad (1)$$

183 for translational motion, where F_i is the resultant force (the sum
 184 of the all externally applied forces acting on the particle) in N,
 185 m is the total mass of the particle in kg, \ddot{x}_i is the acceleration of
 186 the particle in m s^{-2} and g_i is the gravity loading in m s^{-2} .

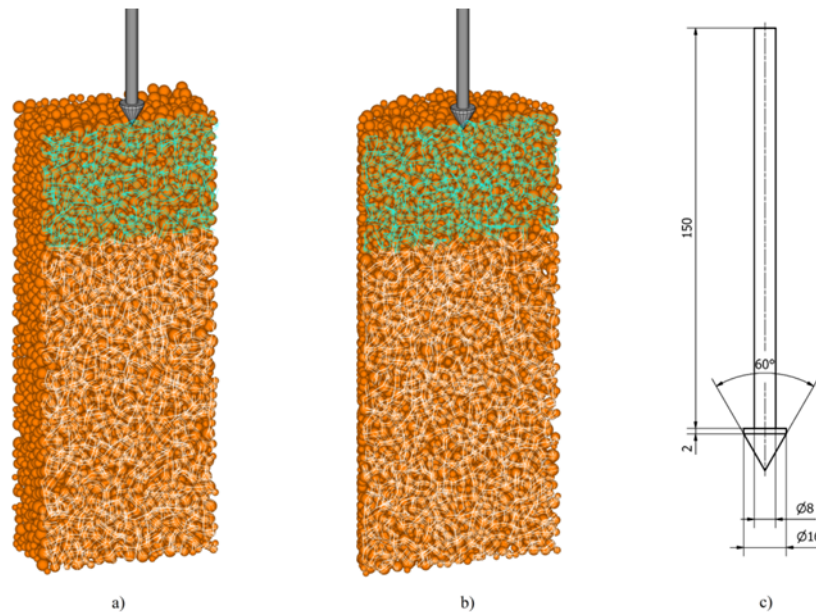
187 For rotational motion, the following equations were used,
 188 which can be written when the particle's local coordinate
 189 system lies along the principal axes of inertia of the particle:

$$\begin{aligned} M_1 &= I_1 \cdot \dot{\omega}_1 + (I_3 - I_2) \cdot \omega_3 \cdot \omega_2 \\ 190 \quad M_2 &= I_2 \cdot \dot{\omega}_2 + (I_1 - I_3) \cdot \omega_1 \cdot \omega_3 \\ M_3 &= I_3 \cdot \dot{\omega}_3 + (I_2 - I_1) \cdot \omega_2 \cdot \omega_1 \end{aligned} \quad (2)$$

191 where M_1 , M_2 , M_3 are the components of the resultant moment
 192 acting on the particle referred to the principal axes in N m, I_1 ,
 193 I_2 , I_3 are the principal moments of inertia of the particle in
 194 kg m^2 and $\dot{\omega}_1$, $\dot{\omega}_2$, $\dot{\omega}_3$ are the angular accelerations about the
 195 principal axes in rad s^{-2} . These two vector equations are
 196 integrated using the centred finite difference procedure
 197 involving timestep of Δt , resulting the velocities (translational
 198 and rotational), which are used to update the positions and the
 199 structure of the particles. Finally, the whole iteration process is
 200 repeated from the beginning so that the displacements of the
 201 elements can be calculated in every timestep.

202 The DEM simulations of soil penetration were performed with
 203 rectangular and circular cross section models (Fig. 1). During
 204 DEM model construction several steps were followed to set up
 205 the final model. Firstly, a huge number of particles (in the
 206 range of 3378 to 24585 depending on the model's dimensions)
 207 were generated in the rectangular and circular shapes of soil
 208 body and poured to the bottom under earth gravity. The

209 geometry of the soil body was changed in each simulation to
 210 investigate the effect of the soil body dimensions and shape on
 211 soil penetration resistance. The diameters of the circular cross
 212 sections were chosen so as to provide the same area of that of
 213 the rectangular cross section models, as to allow for correct
 214 comparison between the two models output. Thus, the area of
 215 the rectangular cross section model was 0.06 m by 0.06 m
 216 which was equal to the circular cross section model with a
 217 diameter of $\varnothing 0.0677$ m and so on. The area ratio calculated as
 218 the ratio of the area of the model's cross section divided by the
 219 projected area of the penetrometer cone (0.0002 m^2) was
 220 considered for further analysis to understand the effect of the
 221 shape and size of the model's cross section on penetration
 222 resistance. Finally, the height of the soil model was changed for
 223 0.2 m, 0.25 m, 0.3 m and 0.35 m. The height ratio calculated by
 224 dividing the model's height with the penetration depth (0.15 m)
 225 was also considered in the simulation. Figure 1 illustrates the
 226 initial geometry of two individual models where only one half
 227 of the model is shown to visualise the parallel bonds in the
 228 central plan. In this figure the dimensions of the cone
 229 penetrometer used in the simulation can be seen as well.
 230



231
 232 Figure 1. The three-dimensional (3D) discrete element model (DEM) initial
 233 geometry of the rectangular cross section (a) with a model dimension of
 234 0.12 m by 0.12 m by 0.30 m, the circular cross section (b) with a model
 235 dimension of $\varnothing 0.1354$ m by 0.30 m and the dimensions of the cone
 236 penetrometer in mm (c). Parallel bond contacts are represented as white and
 237 cyan lines in the central plan of the models in (a) and (b).

238 After the DEM model was established, the contact properties of
 239 soil particles shown in Table 2 were assigned between the
 240 elements. In PFC3D code, the contacts between the elements

241 play an important role because only rigid elements can be
 242 generated. Therefore, the material properties can be modelled
 243 correctly if sufficient contact and accurate contact parameters
 244 are assigned between the particles. To simulate the interaction
 245 between particles of real soil, the Linear Model and Parallel
 246 Bond Model available in the PFC3D code were used. The
 247 Linear Model was responsible to represent the friction between
 248 the particles. Therefore in each contact, the contact force vector
 249 (F_i) can be resolved into normal (F_i^n) and shear (F_i^s)
 250 components with respect to the contact plane defined by the
 251 unit vectors (n_i and t_i) as follows (Potyondy and Cundall,
 252 2004):

$$253 \quad F_i = F_i^n \cdot n_i + F_i^s \cdot t_i . \quad (3)$$

254 The normal component (F^n) of the contact force can be
 255 calculated by (Potyondy and Cundall, 2004):

$$256 \quad F^n = K^n \cdot U^n \quad (4)$$

257 where K^n denotes the normal stiffness between the contacting
 258 elements in N m^{-1} and U^n is the overlap of the contacting
 259 elements in meter. The new shear force (F^s) at the end of the Δt
 260 timestep can be calculated in an incremental fashion with the
 261 shear elastic force increment (ΔF^s) using the following formula
 262 (Potyondy and Cundall, 2004):

$$263 \quad F^s = F_{old}^s + \Delta F^s \leq \mu \cdot F^n = F_{max}^s \quad (5)$$

264 where F_{old}^s is the shear force from the previous timestep in N
 265 and μ is the dimensionless friction coefficient between the
 266 particles. If the new shear force is greater than the maximum
 267 allowable shear contact force (F_{max}^s) slip is allowed to occur in
 268 the next timestep between the contacting elements. The shear
 269 elastic force increment can be determined with the contact
 270 shear stiffness (k^s) and the shear displacement increment (ΔU^s)
 271 occurring over a timestep of Δt (Potyondy and Cundall, 2004):

$$272 \quad \Delta F^s = -k^s \cdot \Delta U^s . \quad (6)$$

273 The only difference between Formula 4 and Formula 6 is that
 274 the shear force is calculated in increment form with the tangent
 275 stiffness modulus (k^s) in each timestep, while the normal
 276 contact force relates the total displacement and total force of
 277 the particle, which can be interpreted with the numerical
 278 stability. The computation of the normal force only from the
 279 geometry makes the code less prone to numerical drift
 280 (Potyondy and Cundall, 2004).

281 The cohesive behaviour of the soil was simulated by the
 282 Parallel Bond Model which was developed by Cundall and
 283 Potyondy (2004). When a parallel bond is defined between the
 284 contacting particles, force- and moment increment vectors are
 285 developed in the contact similarly to that in case of Linear
 286 Model and were summed to the corresponding force and
 287 moment components. In addition, there are maximum tensile
 288 (σ_{max}) and shear stresses (τ_{max}) acting on the parallel bond area
 289 (Potyondy and Cundall, 2004):

$$\begin{aligned}
 \sigma_{max} &= \frac{-\overline{F}^n}{A} + \frac{|\overline{M}^s|}{I} \cdot \overline{R} \\
 \tau_{max} &= \frac{|\overline{F}^s|}{A} + \frac{|\overline{M}^n|}{J} \cdot \overline{R}
 \end{aligned}
 \tag{7}$$

291 where $\overline{F}^n, \overline{F}^s, \overline{M}^s, \overline{M}^n$ are the normal- and shear contact force
 292 in N, axial- and shear directed moments in N m, respectively.
 293 A, I and J denote to the area in m^2 , the moment of inertia and
 294 the polar moment of inertia of the parallel bond cross section in
 295 m^4 , respectively. If the maximum normal stress exceeds the
 296 parallel bond normal strength or the maximum shear stress
 297 exceeds the parallel bond shear strength the parallel bond
 298 breaks between the two contacting elements (Potyondy and
 299 Cundall, 2004).

300 To implement these two contact models, the contact properties
 301 (shown in Table 2) between the soil particles need to be
 302 determined to give accurate results in soil penetration resistance
 303 compared to the in-situ measurements. The values of the
 304 normal and shear ball stiffness were assumed equal. After that a
 305 large number of simulations were performed with manually
 306 modified contact properties to investigate the effect of the
 307 individual parameters (ball stiffness and the parallel bond
 308 strengths and stiffness) on the penetration resistance. After each
 309 simulation the calculated soil penetration resistances were
 310 compared to the measurement values and the contact
 311 parameters were modified to provide similar soil resistance
 312 variations to that of the in-situ. This was repeated
 313 approximately the 60th to achieve convergence. The results of
 314 the calibrational process are shown in Table 2.

315 Table 2. The material properties of the discrete element models (DEM),
 316 derived from the DEM penetration simulations.

Parameter	Value
Bulk density ($kg\ m^{-3}$)	1632
Particle radius distribution (m)	0.002-0.0045
Porosity (%)	0.413...0.439

Ball normal stiffness (kn) (N m^{-1})	1e6
Ball shear stiffness (ks) (N m^{-1})	1e6
Penetrometer normal stiffness (N m^{-1})	1e10
Penetrometer shear stiffness (N m^{-1})	1e10
Local damp constant (α) (-)	0.3
Friction coefficient between ball and ball (μ_{ball}) (-)	0.6
Friction coefficient between ball and cone penetrometer (μ) (-)	0.5
Timestep range (s)	1.9e-6-2.6e-6
<i>Parallel Bond parameters (results of the iteration)</i>	
Parallel Bond radius (pb_rad) (-)	0.5
Parallel Bond normal stiffness (pb_kn) (Pa m^{-1})	5.25e7
Parallel Bond shear stiffness (pb_ks) (Pa m^{-1})	5.25e7
Parallel Bond normal strength in the top layer (pb_n) (Pa)	4.27e5
Parallel Bond shear strength in the top layer (pb_s) (Pa)	4.27e5
Parallel Bond normal strength in the bottom layer (pb_n) (Pa)	6.4e5
Parallel Bond shear strength in the bottom layer (pb_s) (Pa)	6.4e5

317

318 The soil model was divided into two sections. In the top section
319 down to 0.08 m depth, the parallel bonds were assigned smaller
320 normal- and shear strength, whereas elements in the bottom
321 layer were assigned higher material parameters (Table 2 and
322 Fig. 1). This was done in order to simulate the actual soil
323 strength encountered in the field, where the top layer is
324 subjected to lower normal stresses as compared to deeper
325 layers.

326 The cone penetrometer was placed on the top of the soil
327 surface, and was moved downwards throughout the soil body
328 down to 0.15 m depth with the same velocity as in the in-situ
329 measurements (0.01 m s^{-1}), while soil resistance to penetration
330 was calculated at each 1000th calculation cycle. The timestep
331 was set to “auto” to guarantee the mathematical stability of the
332 calculation (Itasca, 1999). Thus the value of the timestep was
333 automatically modified in every calculation timestep, within
334 approximate range of $1.9 \cdot 10^{-6}$ - $2.6 \cdot 10^{-6}$ s.

335 Spherical elements were used in the calculations. It is well
336 known that the shape of the particles plays an important role in
337 the DEM simulations (Falagush et. al., 2015 and

338 Nakashima et al., 2013). In our simulations the Parallel Bond
339 contact force presents (cohesive soil) to capture the rotational
340 resistance of the spherical elements in the simulations.

341 *2.3. Discrete element model of direct shear test*

342 In earlier research by Tamás et al. (2013) and Sadek et al.
343 (2011), direct shear tests were simulated to determine the
344 mechanical parameters of the soil, namely, Mohr-Coulomb
345 properties of cohesion and angle of internal friction. Similar
346 approach was adopted in the current work. DEM simulations of
347 the direct shear tests were performed to estimate the soil
348 cohesion and internal friction angle. Comparison between the
349 simulation and laboratory tests results could not to be done
350 because direct shear tests were not performed at the time of
351 penetration resistance measurements. The estimation of the
352 soil's mechanical properties was done based on Mohr-Coulomb
353 law, which describes a linear relationship between the
354 maximum of the horizontal (shear) (T_f) and the normal forces
355 (N) (Terzaghi, 1943):

$$356 \quad T_f = c \cdot A + N \cdot \tan \varphi \quad (8)$$

357 where c refers the cohesion in MPa, A is the sheared area in
358 mm^2 and φ means the angle of internal friction of the soil
359 sample in degree $[\circ]$.

360 The dimension of the shear box test was set to be of
361 0.06 m by 0.06 m by 0.0508 m so that the area of the cross
362 section was 0.06 m by 0.06 m = 0.0036 m^2 . The same contact
363 properties were set in the simulation to that of used in the soil-
364 penetration simulations. The top half of the soil sample in the
365 shear box was subjected to downward vertical forces (e.g. the
366 normal force, N), while the top section was moved horizontally,
367 as shown in Fig. 2. In this figure the parallel bonds were
368 represented as white lines. During the simulations the
369 horizontal and vertical displacement of the box and the shear
370 force (T) were calculated at each 500th calculation cycle. The
371 DEM simulations of the direct shear test were performed with
372 the top layer of the soil model (assigned parallel bond strength
373 of 4.27e5 Pa (Table 2) subjected to normal loads of 480 N,
374 615 N, 750 N and 885 N, respectively. The calculations were
375 performed with the bottom soil model layer assigned larger
376 parallel bond strength of 6.4e5 Pa (Table 2) as well.

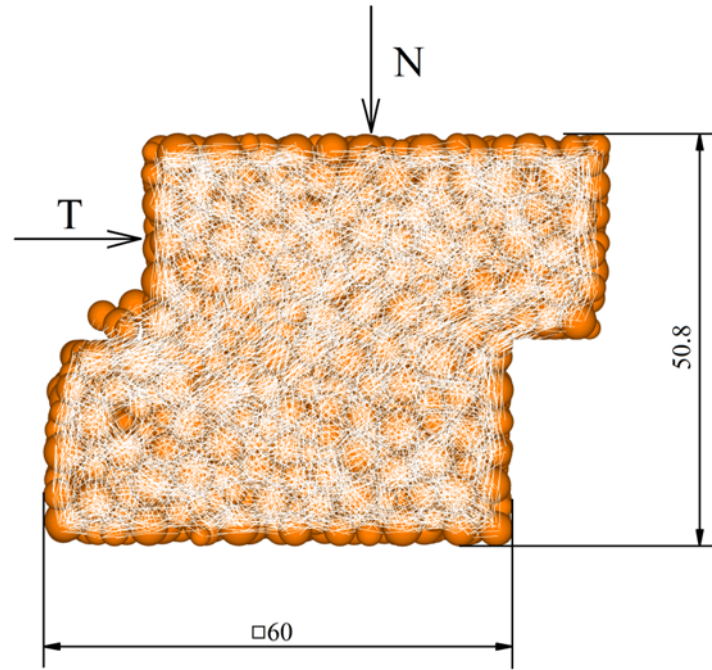
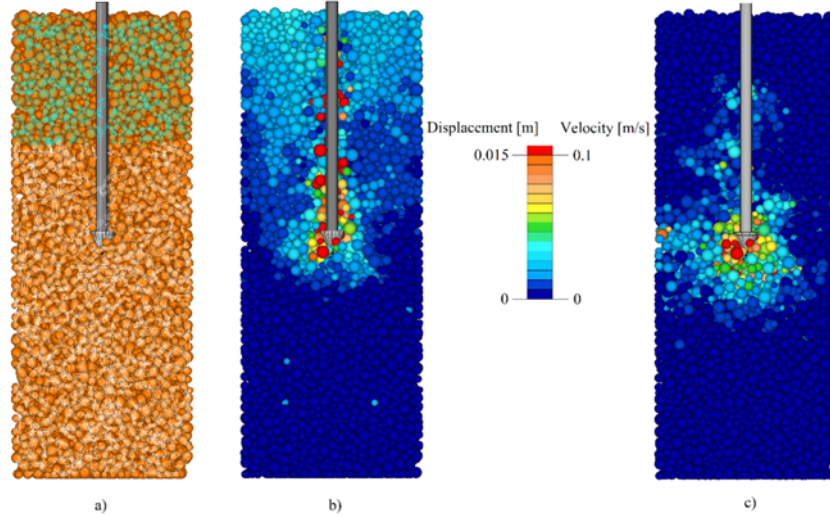


Figure 2. Discrete element method (DEM) simulation of the direct shear box test. Parallel bond contacts are represented as white lines and the dimensions are in mm.

3. Results and discussion

3.1. Qualitative estimation of the soil penetration

According to the experimental work, the maximum displacement of the soil particles takes place near and ahead of the cone penetrometer (Tanaka et al., 2000 and Foster Jr. et al., 2005). The DEM output for displacement, shown in Fig. 3b shows a similar pattern of particles movement to that of the experiment. According to Tanaka et al. (2000) the elements near the penetrometer cone and shaft moved downward following the movement of the penetrometer because of the high coefficient of friction value between the soil particles and the cone penetrometer. A maximum displacement of 0.015 m was calculated for few elements that are in direct contact with the penetrometer cone and shaft. It was predictable as well that the particles' greatest velocity at given timestep will be around the head of the cone, which can be observed in Fig. 3c. Figure 3a also shows the broken parallel bonds in front of and near the head of the penetrometer cone due to the failure of these bonds by the forces exerted by the penetrometer cone. The soil failure process under the tip of the penetrometer cone is not known in detail but it can be assumed that the soil failures occur approximately where the parallel bonds break in the discrete element model.



404

405 Figure 3. The result of the discrete element method (DEM) numerical
 406 simulation of the penetration test, shown for a rectangular cross section with
 407 a soil body cross-section of 0.12 m by 0.12 m and height of 0.30 m: a) front
 408 view of the DEM model, showing the broken parallel bonds, b) elements
 409 displacement distribution and c) elements velocity distribution.

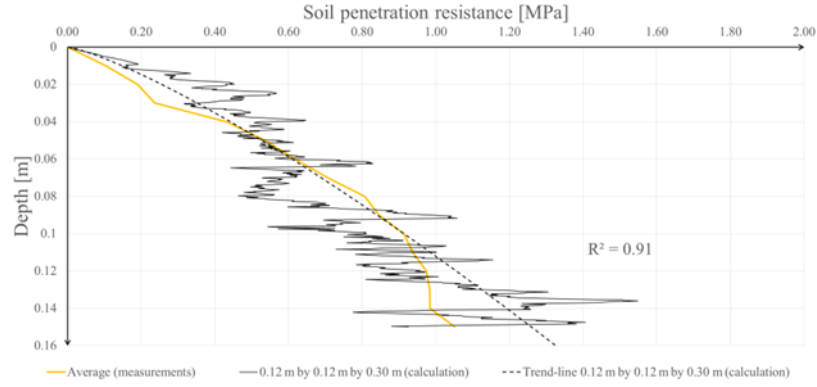
410 3.2. Quantitative estimation of the soil penetration resistance

411 The calculated soil penetration resistance was illustrated as a
 412 function of the cone's vertical displacement, which can be
 413 observed in Fig. 4 for a rectangular cross section of
 414 0.12 m by 0.12 m and a height of 0.30 m. Results show that the
 415 calculated penetration resistance matches the average measured
 416 soil resistance, which indicates a realistic model approximation
 417 of in-situ soil penetration.

418 Similar to previous works (Tanaka et al., 2000 and Foster Jr.
 419 et al., 2005), the simulated penetration resistance fluctuated
 420 considerably, with larger fluctuation observed with increased
 421 depth (Foster Jr. et al., 2005). The reason of this result could be
 422 the large diameter of the soil particles (Tanaka et al., 2000).
 423 The number of contacting elements with the tip of the cone was
 424 counted as well in order to check to get enough balls around the
 425 tip and correct soil resistance variations, this data varied in the
 426 range of 10...20 in the simulations. To investigate the accuracy
 427 of the individual simulations a trend-line calculated using the
 428 Ordinary Least Squares available in the Microsoft Excel 2013
 429 software was fitted to the simulation values, with a high R^2
 430 value of 0.91. The mean error (\overline{RE} in %) of the trend-line and
 431 the average soil penetration resistance was calculated according
 432 to Sadek et al. (2011):

$$433 \quad \overline{RE} = \frac{\sum_{i=1}^n \frac{CI_{DEM} - CI_{in-situ}}{CI_{in-situ}}}{n} \cdot 100 \quad (9)$$

434 where the CI_{DEM} is the soil resistance calculated from the trend-
 435 line of the DEM simulation in MPa, $CI_{in-situ}$ is the measured
 436 average soil resistance from the in-situ tests in MPa and n is the
 437 number of depth where the soil resistance values were
 438 measured ($n=15$ in this case). In the later sections these trend-
 439 lines were compared with the measured average values of the
 440 penetration resistance.

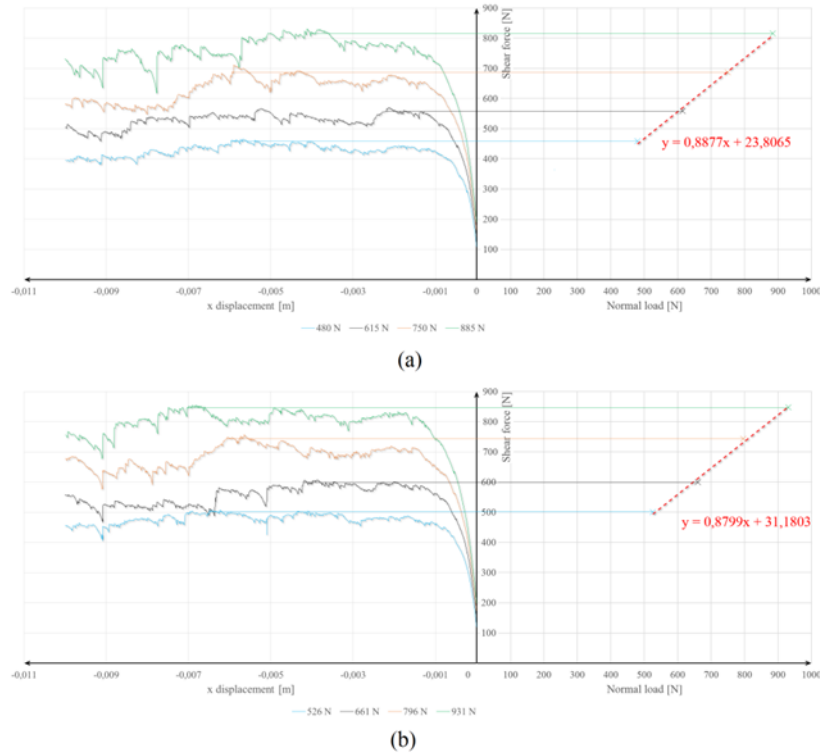


441

442 Figure 4. Variation in the discrete element method (DEM) simulation of the
 443 penetration test, shown for a rectangular cross section model with a cross-
 444 section of 0.12 m by 0.12 m and a height of 0.30 m.

445 3.3. Numerical simulation of the direct shear tests

446



447

448 Figure 5. The force-displacement relationship calculated from the discrete
 449 element method (DEM) simulation of the direct shear tests for the bottom
 450 (a) and top (b) sections of the soil model.

Figure 5 shows the DEM calculated force-displacement relationship of the direct shear tests for the bottom and top soil sections. The value of the shear force fluctuated similar to the work of Tamás et al (2013) and to the soil resistance in the 3D DEM simulations of penetration (Fig. 4). In order to calculate the mean of the maximum shear force, the force values were averaged in the 0.00025 m radius vicinity of the displacement where the maximum shear force takes place. From the mean of the maximum shear- and normal force values, the Coulomb line of the soil model layers can be drawn. Although the Coulomb line for the top and bottom layers are similar the cohesion component of the bottom layer (8.66 kPa) was larger than that of the top layer (6.61 kPa), while the friction angle was very similar (41.34° and 41.60°), respectively. This result is in line (for cohesion only) with Mouazen and Neményi (1999) reported increase in the cohesion and internal friction angle values with depth.

Another result of the 3D DEM direct shear simulations is that the parallel bond's strength contact parameter does not have large effect on the calculated cohesion and angle of internal friction.

3.4. *The effect of the shape of the model's cross section*

The comparison between the DEM calculated (with both cross-section models) and field measured penetration resistance is shown in Fig. 6.

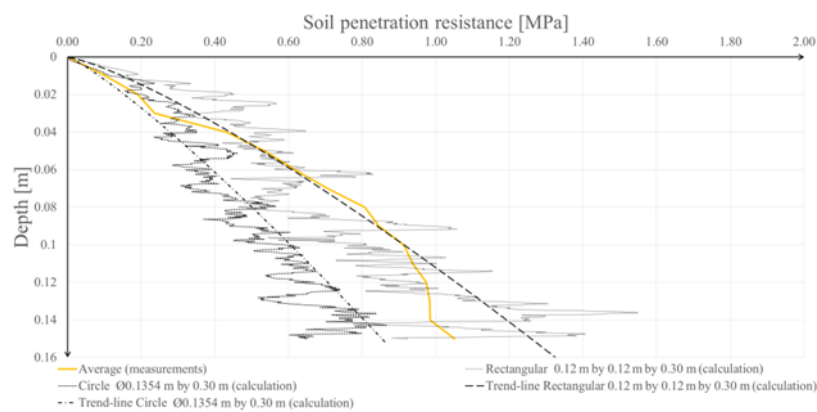
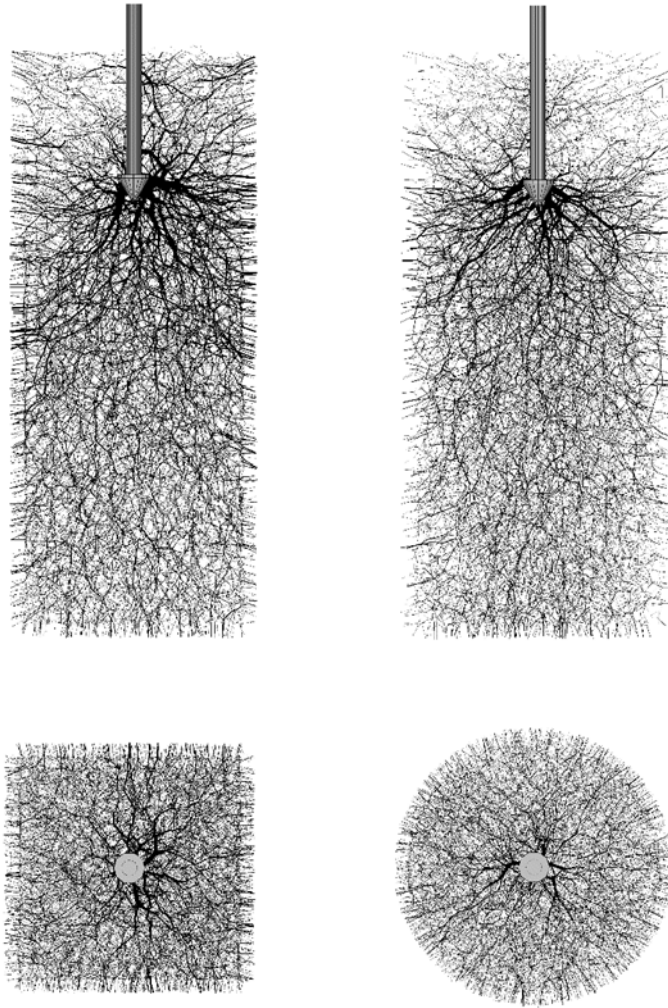


Figure 6. The effect of the discrete element model (DEM) soil model cross-section shape on calculated penetration resistance.

It can be clearly observed that the soil resistance calculated with the rectangular cross section is higher than that of the corresponding values calculated with the circular cross-section model. This can be explained by examining the distribution of the contact forces between the particles, shown in Fig. 7 for a rectangular model of 0.12 m by 0.12 m by 0.30 m and a circular model of Ø0.1354 m by 0.30 m and for a penetration depth of

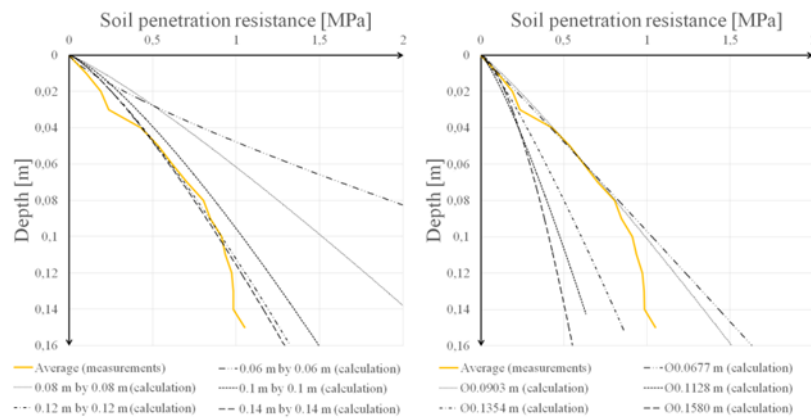
0.78 m where simulations gave approximately the same soil resistance value (see Fig. 6). The linewidth of the contact lines is proportional to the magnitude of the force between the particles. It was scaled up to 31 N in both cases, which means that the greatest linewidth represents the contact force of 31 N or higher between the contact elements. Figure 7 shows greater contact forces near the tip of the penetrometer cone in the rectangular cross-section model as compared to the circular cross-section model, because there are more thick lines (meaning greater contact forces) in the former case than in the latter model. This can be possible because of the local damping between the particles and because of the models' boundary condition, namely the position of the side wall of the models. The distance between the tip of the cone penetrometer and the side wall is $0.12 / 2$ m in the rectangular soil model, and $0.1354 / 2$ m in the circular model. Therefore, in the case of the circular model a larger distance to the wall exists, so that the effect of the cone's motion on particles stresses is lower, as the particles have more freedom to move towards the wall as compared to the rectangular model. This can cause smaller calculated soil resistance in case of the circular cross-section model as compared to that of the rectangular one with same area ratio (same volume).



509

510 Figure 7. The distribution of the contact forces calculated with the discrete
 511 element method simulation for a rectangular (left –
 512 0.12 m by 0.12 m by 0.30 m) and circular cross-section (right –
 513 $\varnothing 0.1354$ m by 0.30 m) models of the same volume.

514 3.5. The effect of the size of the soil model's cross section



515

516 Figure 8. The effect of the discrete element model (DEM) model cross
 517 section size on calculated penetration resistance calculated for the
 518 rectangular shape (left) and for the circular shape soil models (right).

Figure 8 shows the results of the effect of the cross section size on penetration resistance, calculated from the DEM for the rectangular and circular cross-section models. In case of the smaller cross section models, the penetration resistance values were larger in both soil model shapes than that of the larger cross section models, because the boundary walls were too close so that the balls were constrained from moving away from the head of the cone penetrometer. In case of rectangular cross section model, the DEM simulations with area ratio of 50, 72 and 98 (cross section size of 0.10 m by 0.10 m, 0.12 m by 0.12 m and 0.14 m by 0.14 m, respectively, see Table 3) resulted in similar but smaller soil resistance values than that of a cross section of 0.06 m by 0.06 m and 0.08 m by 0.08 m (Fig. 8). It could be concluded that either rectangular model with area ratio of 72 and 98 approximate the measured soil resistance with reasonable accuracy with mean relative errors of 14.91 % and 16.69 %, respectively (Table 4).

Table 3. The geometrical parameters of the three dimensional (3D) discrete element soil models.

Size of the cross section [m]	Area [m ²]	Area ratio [-]
0.06 by 0.06 Ø0.0677	0.36e-2	18
0.08 by 0.08 Ø0.0903	0.64e-2	32
0.10 by 0.10 Ø0.1128	1.00e-2	50
0.12 by 0.12 Ø0.1354	1.44e-2	72
0.14 by 0.14 Ø0.1580	1.96e-2	98

Model's height [m]	Penetration depth [m]	Height ratio [-]
0.20	0.15	1.33
0.25		1.67
0.30		2.00
0.35		2.33

Table 4. The mean error of the DEM penetration simulations.

Cross section dimension (m)	Area ratio (-)	Height ratio (-)	Coefficient of determination (R ²) (-)	Mean relative error (%)
0.06 by 0.06 by 0.30	18	2.00	0.89	152.19
0.08 by 0.08 by 0.30	32	2.00	0.91	78.81

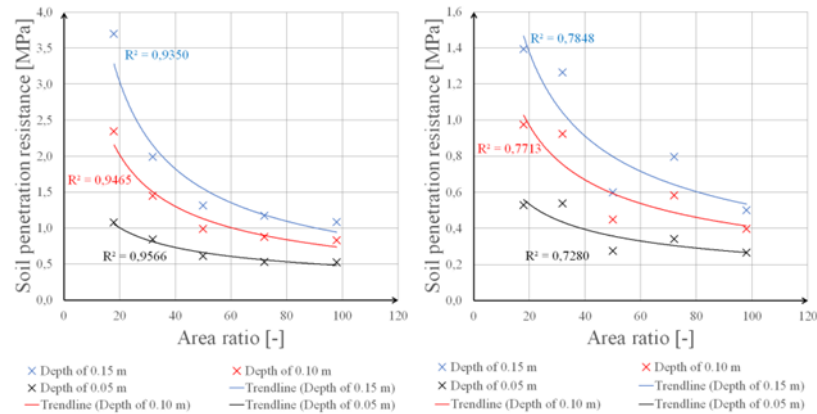
0.10 by 0.10 by 0.30	50	2.00	0.89	27.94
0.12 by 0.12 by 0.20	72	1.33	0.87	14.74
0.12 by 0.12 by 0.25	72	1.67	0.76	31.99
0.12 by 0.12 by 0.30	72	2.00	0.91	14.91
0.12 by 0.12 by 0.35	72	2.33	0.85	22.13
0.14 by 0.14 by 0.30	98	2.00	0.84	16.69
Ø0.0677 by 0.30	18	2.00	0.90	15.06
Ø0.0903 by 0.30	32	2.00	0.86	14.92
Ø0.1128 by 0.30	50	2.00	0.87	42.24
Ø0.1354 by 0.20	72	1.33	0.77	30.10
Ø0.1354 by 0.25	72	1.67	0.84	31.63
Ø0.1354 by 0.30	72	2.00	0.92	28.05
Ø0.1354 by 0.35	72	2.33	0.93	34.03
Ø0.1580 by 0.30	98	2.00	0.91	45.01

540

541 According of Fig. 8 for the simulation with the circular cross
542 section soil model, similar tendency of results to that of the
543 rectangular shape model could be observed. The highest
544 penetration resistance was observed with the smallest cross
545 section size model, which reduced with the increase in the cross
546 section size. However, a minor deviation was observed for the
547 resistance calculated for the area ratios between 50 and 72,
548 where although very similar results were observed a slightly
549 greater resistance was calculated for the latter case. This can be
550 interpreted by the geometrical differences between the
551 simulations, namely the different ball positions and ball
552 radiuses. It is possible that the cone does not get into contact
553 with so many particles in one simulation than it does in the
554 other, which affects its calculated resistance. For the circular
555 models with area ratio of 50, 72 and 98, the calculated
556 penetration resistance variations with depth were smaller than
557 the in-situ measured variations, which suggests that these
558 models are not useful for approximating the measured
559 penetration resistance. The best DEM model that can be
560 recommended to approximate the in-situ measurement is the
561 model with area ratio of 32 with a mean relative error of
562 14.92 % (Fig. 8 and Table 4), after which the model with area
563 ratio of 18 is considered as the second best performing model
564 with a mean relative error of 15.06 %.

565 Our expectation was that if the size of the cross section of the
566 soil model is increased the soil penetration resistance should
567 decrease because the freedom of the elements' movement
568 increases. But, if the cross section size is large enough and
569 subsequently the area ratio then the DEM simulation results
570 should not change anymore because the boundary of the model

571 is far away enough to have an effect on penetration resistance.
 572 Therefore, the rectangular and circular soil body should give
 573 similar results in penetration resistance. According to the
 574 results in the former section the circular models always gave
 575 smaller soil resistance values than that of the rectangular soil
 576 models. This means that there is an effect of the soil body
 577 boundary in case of soil model with the greatest area ratio (98).
 578 This can be seen in Fig. 9 where the soil penetration resistance
 579 at depth of 0.15 m, 0.10 m, 0.05 m (e. g., CI index) were
 580 illustrated as the function of area ratio (e. g., the size of the
 581 models cross section) in case of rectangular shape (left) and
 582 circular shape soil models (right), respectively. In case of
 583 rectangular shape the coefficient of determination value were
 584 high (> 0.93) and the penetration resistance decreased with
 585 increasing area ratio but it can be smaller because the trend-
 586 lines were not approximate their asymptotes with sufficient
 587 accuracy. Similar to that can be said in case of circular model
 588 shape where the R^2 values of trend-line fitting were smaller
 589 than in the former case. Therefore, the area ratio should be
 590 increased but in this case more particles are needed to perform
 591 the simulation and this will increase the computational time
 592 dramatically in the future. In such simulations one should
 593 expect the need for several million elements, which will cause
 594 unacceptable computational time and the simulations will be no
 595 more useful.



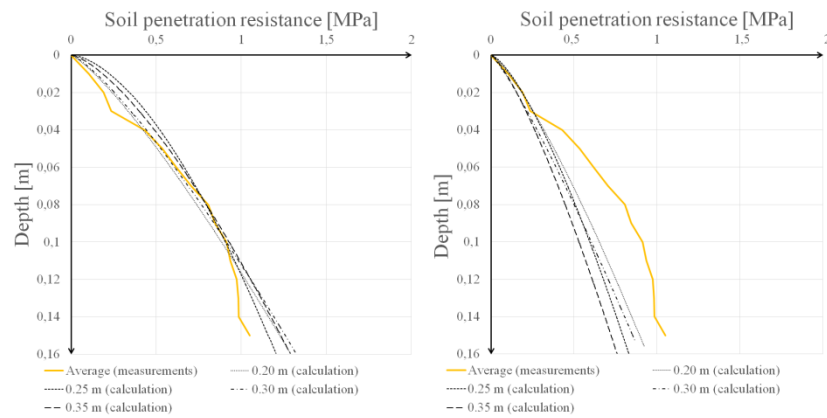
596
 597 Figure 9. The effect of the discrete element method (DEM) model cross
 598 section size on penetration resistance calculated for the rectangular shape
 599 (left) and for the circular shape soil models (right).

600 Summarizing the results it can be said that the best
 601 approximating DEM soil model to the in-situ penetration
 602 resistance measurements was the rectangular model with area
 603 ratio of 72 (a mean relative error of 14.74 %). However the
 604 mean error of the best performing circular model (with area
 605 ratio of 32) was slightly smaller than that of the rectangular
 606 model with area ratio of 72 (see Table 4). The advantage of the

607 circular cross section models was that they gave accurate
 608 results with smaller area ratio (smaller volume) than the
 609 rectangular models did. Therefore, from practical point of view,
 610 it is recommended to adopt the circular shaped models, since
 611 smaller number of particles need to be used in the simulation
 612 and the calculation time can be minimized, as this depends on
 613 the number of the elements (Hanley et al, 2014).

614 3.6. Effect of soil model's height

615 As stated earlier that the DEM simulations were performed
 616 with height ratios of 1.33, 1.67, 2 and 2.33 to analyse the effect
 617 of the model's height on calculated penetration resistance. The
 618 results of these simulations for the rectangular and circular
 619 cross section models are shown in Fig. 10 a and b, respectively.
 620 It can be observed that the model's height does not have
 621 considerable effect on the calculated soil penetration resistance
 622 at the range of height ratio between 1.33 and 2.33. Therefore
 623 similar conclusion can be drawn to that of the former section,
 624 that from practical point of view, it is recommended to adopt
 625 the smallest height ratio of 1.33, since smaller number of
 626 particles are need to be used in this simulation and the
 627 calculation time can be minimized.



628
 629 Figure 10. The effect of the discrete element model (DEM) model height on
 630 calculated penetration resistance for the rectangular (left) and circular (right)
 631 cross section soil model.

632 4. Conclusions

633 This paper used the discrete element method (DEM) to
 634 simulate the penetration of a slightly cohesive soil with a
 635 standard cone penetrometer, aiming at optimising the soil
 636 model geometry for the best estimations of penetration
 637 resistance that match the corresponding in-situ measurements.
 638 After the calibration of the contact properties of the discrete
 639 element model the soil mechanical properties, namely,
 640 cohesion and internal friction angle were estimated by DEM
 641 simulation of direct shear box tests.

Results showed that the DEM can be successfully used to simulate the penetration in a cohesive soil, as the DEM calculations were in good agreement with the measured values. The DEM calculations of the penetration resistance, calculated with the circular cross section soil model were always smaller than those calculated with the rectangular model. The DEM model outputs with the rectangular cross section showed that the model with an area ratio of 72 (cross section = 0.12 m by 0.12 m) or 98 (cross section = 0.14 m by 0.14 m) provided the most accurate estimation of penetration resistance with a mean relative error of 14.91 % and 16.69 %, respectively when compared to the in-situ measurement. For the circular cross section model, the model with an area ratio of 32 (diameter = Ø0.0903 m) followed by 18 (diameter = Ø0.0677 m) performed the best with mean relative errors of 14.92 % and 15.06 %, respectively when compared to the in-situ measurement. The DEM simulations of the optimal height ratio showed the model's height have a negligible effect on the calculated soil penetration resistance in the range of height ratio between 1.33 and 2.33. Therefore, it is possible to recommend these DEM model parameters as the best results of DEM simulation of soil penetration with a standard cone penetrometer.

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