CONE PENETRATION TEST IN A VIRTUAL CALIBRATION CHAMBER

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8.1 Introduction

In this chapter the micro/meso response of the VCC CPT models during cone penetration is investigated in detail. Individual particles and their interactions during cone penetration are considered. This chapter contributed to the article 12 from the Publications list (pp. ix-x).

Two penetration depths were selected, viz. shallow penetration at normalized vertical distance \((\frac{z-H_{vc}}{d_c})\) equal to -1.4 \((h_p \approx 0.1 \text{ m})\) and deep penetration at \((\frac{z-H_{vc}}{d_c})\) equal to -5.6 \((h_p \approx 0.4 \text{ m})\). It must be pointed out that the deformation measure is related to the original (undeformed) reference configuration (before CPT, initial stage). Moreover, results are plotted for tests characterized with different stress history, relative density and boundary conditions. Detailed information about the tests included in this chapter can be seen in Table 31.

The micro response of the VCC CPT model will be examined by looking at (i) the displacement field around the cone, (ii) the normal contact force distribution, and (iii) different components of the stress tensor. The soil fabric is presented as the orientation of normal contact forces and their changes during penetration process. However, the raw results from DEM analysis (interparticle forces and displacements) have little purpose if we cannot correlate them with continuum mechanics parameters, like stresses and strains. To be able to ‘translate’ discrete results into continuum ones transformation (interpolation or homogenization) methods are required. The methods to convert contact forces into stresses are straightforward and well defined (static averaging) while there is no unique method to convert displacements into strains (kinematic averaging). The definition and computation of stress chosen here is that proposed by Itasca Consulting Group Inc. [2008] while a non-local meshfree interpolation approach for strain calculation proposed by O’Sullivan et al. [2003] is applied to map the evolution of strain in the virtual calibration chamber (VCC) as the penetration proceeds. Both averaging processes are described in Chapter 4. As a results of the stress averaging process, the stress paths and rotation of the major principal stress \((\sigma_1)\) can be also analyzed.

For each spherical particle, the PFC\textsuperscript{3D} program computes its identification number (ID), radius \((r)\), current position \((p(x_0, y_0, z_0))\), stress matrix \((\sigma_{ij})\), contact with other body (particle or wall) and contact force matrix \((F_{ij})\) after every time-step increment. In this analysis, to reduce data storage, all these informations were recorded every 14500 steps (= 0.02m of cone penetration). Next, all results were used for the micromechanical analysis via. graphical and/or statistical presentation.

The five tests (detailed in the Table 31) that are examined here allow us to study the effect of four different model traits on the micro response of cone penetration always for two different penetration depths viz. shallow and deep penetration:
influence of the specimen initial density: T16 and T20-Figure 164a. Tests with two different initial relative densities, 75 and 90\%, respectively are chosen. Both test are prepared at the isotropic stress state of 100 kPa.

influence of the different boundary conditions (BC1 and BC3): T163 and T164-Figure 164b. Tests with two different radial boundary conditions, viz. BC1 (σv and σh are constant) and BC3 (σv is constant and εh is equal to 0), are selected. These tests are performed on a material with DR=94.6\% at stress states resulting from anisotropic consolidation (K0-conditions).

influence of the stress state (isotropic vs. anisotropic): T20 and T163-Figure 164c. Tests that differ in the stress system applied during the consolidation stage (isotropic and anisotropic) but prepared to similar horizontal stress are selected for this analysis.

influence of particle rotation: T16 and T16Rot-Figure 164d. Tests that differ in the particle rotation properties but prepared to relative density of 75\% an isotropic stress of 100 kPa are chosen for to examine this issue.

Table 31: List of tests used in microanalysis

<table>
<thead>
<tr>
<th>ID</th>
<th>D_R</th>
<th>σ_z</th>
<th>σ_h</th>
<th>BC</th>
<th>q_c,lim</th>
<th>NickName</th>
</tr>
</thead>
<tbody>
<tr>
<td>T16</td>
<td>75</td>
<td>100</td>
<td>100</td>
<td>BC1</td>
<td>10.36</td>
<td>MediumIsoBC1</td>
</tr>
<tr>
<td>T20</td>
<td>90</td>
<td>100</td>
<td>100</td>
<td>BC1</td>
<td>12.92</td>
<td>DenseIsoBC1</td>
</tr>
<tr>
<td>T163</td>
<td>96.8</td>
<td>313</td>
<td>109</td>
<td>BC1</td>
<td>13.04</td>
<td>DenseKoBC1</td>
</tr>
<tr>
<td>T164</td>
<td>96.8</td>
<td>313</td>
<td>109</td>
<td>BC3</td>
<td>40.8</td>
<td>DenseKoBC3</td>
</tr>
<tr>
<td>T16Rot*</td>
<td>75</td>
<td>100</td>
<td>100</td>
<td>BC1</td>
<td>1.18</td>
<td>MediumIsoRotBC1</td>
</tr>
</tbody>
</table>

8.2 Displacement analysis

8.2.1 Displacement field

Incremental displacement vector of particle (particles within ±x of the projection plane) movements induced by shallow and deep penetration can be viewed in Figure 165-Figure 169. The arrow lengths correspond to the magnitude of displacements in a given plane multiplied by a factor 3. The scaling factor is chosen only for illustration purposes.

It can be appreciated that the granular material is displaced in a very complex way during CPT at every penetration stage. In the following section we will look closely (and separately) at the two cases, viz. shallow and deep penetration.

* particles are allowed to rotate
8.2.1.1 Case 1: shallow penetration

At the shallow penetration stage (Figures 165a, 165b, 166a, 166b, 167a, 167b, 168a, 168b, 169a and 169b), all particles next to the cone tip are pushed downward and sideways to create space for the penetrating cone tip. Some of the particles situated close to the top wall (surface), bottom and radial walls are enforced by the neighboring particles to move upward. This phenomenon is more clearly seen in Figure 170 to Figure 175. Particles that moved upward, downward and with zero displacements are marked with green, yellow and black colors, respectively. Visible differences are observed between simulations in which particle rotation was inhibited (T16, T20, T163 and T164) and in that where particles could rotate freely (T16Rot). In T16Rot particles could roll between each other and hence, create large zones with upward movement (more pronounced in Cut 1). In all tests there are zones just beneath the cone tip (≈ 2d_c) where particles, in general, move downward. The displacement trends are visualized by using stream-line plots\(^2\)(Figure 355).

Particles with zero displacements are observed in all cases but their number is directly connected to the specimen initial density. Hence, zero-displacement particles are observed in large quantity in medium-dense specimens (T16 and T16Rot) and only sporadically in dense samples (T20, T163 and T164).

In general, an important difference was observed in the mechanism of particle displacement during shallow CPT between the samples (i) prepared under BC1 and BC3 boundary conditions and (ii) with restricted particle rotation and free particle rotation. These differences can be verified in Figure 355.

8.2.1.2 Case 2: deep penetration

At deep penetration stage (Figure 165c, 165d, 166c, 166d, 167c, 167d, 168c, 168d, 169c and 169d), the moving cone again showed a great influence on the particles which were close to the tip, but had also a large influence on the particles adjacent to the sleeve. A similar behavior was observed by Jiang et al. [2006b] while analyzing CPT in 2D granular assembly. In all tests, the particles situated just beneath the cone tip, displaced downward and pushed sideways the particles close to the bottom wall. The particles next to cone shaft generally moved downward and sideways.

The lateral boundary condition had a very strong influence in the displacement pattern. In T163 the displacement pattern is clearly downwards and sidewards. In T164, the particles next to the shaft moved sideways and downward and pushed the neighboring particles up to the surface. This can be clearly seen in the Figure 174c, 174d and also in the stream-line plot (Figure 355d). The particles that moved up created a wedge-formations on both sides of the cone.

In T16Rot (Figure 175) the particles that moved up created a characteristic inclined bands on both sides of the cone. Moreover, the particles with downward movements created triangular zones below the cone tip and in the top ‘extremes’ of the sample. In T16 (Figure 173a and Figure 173b), T20 (Figure 173c and Figure 173d) and T163 (Figure 174a and Figure 174b) the particles that moved up were detected mainly close

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\(^2\) A stream line plot is useful for visualizing the flow direction and speed of a vector field. The ‘particles’ (represented by any of the line markers) trace the flow along a particular stream line. The speed of each particle in the plot is proportional to the magnitude of the vector field at any given point along the stream line.
to top and bottom walls, some close to radial wall and few in the zones away from the boundaries, respectively. All these displacement trends are visualized in Figure 356. Similar trends of particle movements under BC1 and BC3 boundary conditions were also observed by Huang and Ma [1994] while performing a numerical study of CPT in 2D granular assemblies. Particles with zero vertical displacements were observed sporadically in all assemblies.

8.2.2 Displacement magnitude

Figure 176-180 present two orthogonal views indicating the magnitude of the total particle displacements observed up until the selected penetration depth is reached. The total displacements were normalized by the cone tip diameter ($d_c = 72.1$ mm). The particles with zero total displacements are outlined in red, while particles that displace more than $d_c$ are outlined in black. The background color corresponds to the magnitude of total normalized displacements and can be read on the color bar.

8.2.2.1 Case 1: shallow penetration

At shallow penetration, the maximum magnitude of total displacements did not reach $0.65d_c$ ($\approx 47$ mm) for all numerical tests. Looking at the colored spheres we observe that particles with higher total displacements indicate a variety of ‘failure’ mechanism viz. half-sphere (T16, T164), elongate half-sphere (T20) and triangular wedge (T16Rot). On the contrary, for T163 no clear characteristic pattern was not observed.

8.2.2.2 Case 2: deep penetration

At deep penetration, the maximum displacements are experienced by those particles close to either the cone tip or the cone sleeve. The maximum magnitude of total displacement did not exceed $1.5d_c$ in all the tests. The mechanisms observed during shallow penetration have spread over to a higher area (volume) in deep penetration. Zones with very low displacements were observed close to radial walls in T164 (under BC3 boundary conditions, where a clear cylindrical expansion pattern is visible) and T16Rot (free particle rotation).

8.2.3 Averaged displacements

Figure 182-183 show average normalized total displacements of the particles calculated over a given volume. The selected volumes are shown in Figure 181–zone 1 (next to the cone), zone 2 (half way between cone and radial wall) and zone 3 (next to radial wall) are $d_c$, $4.2d_c$ and $7d_c$ away from the axis of symmetry of the cone device. In the r-direction/vertical direction the thickness of each zone/layer is equal to 0.1 m.

8.2.3.1 Case 1: shallow penetration

Generally in the shallow penetration phase the horizontal displacements ($u$ and $v$) are much smaller than the vertical displacements ($w$). Moreover, $u$, $v$ and $w$ (as well as the total displacements) decrease as $\frac{r}{R_{vcc}}$ increases. The evolution of $u$ and $v$ with depth in all zones is quite similar and the total magnitude does not reach 0.5% of
d_c. Important differences are observed while looking at the vertical displacements. In zone 1 the direction of displacements is downward with the maximum (T163: -0.12d_c) and minimum (T16Rot: -0.05d_c) values reached just beneath the cone tip. At the bottom of the VCC the displacements are ≈ 0.01d_c for all tests. In zones 2 and 3, visible differences are observed for T163 and T16Rot. For T163 the displacements are ≈ 0.025d_c bigger than in the rest of the tests. For the T16Rot, starting from normalized VCC depth of -2 the particles moved upward, while in the other tests particles always moved down.

8.2.3.2 Case 2: deep penetration

For the deep penetration case, the magnitude of z-motion is much greater than of x- and y-motion. Similar to the results from case 1, all displacements decreased with increasing \( r_i/R_{VCC} \). In zone 1 the z-motion showed a 'hook' shape with maximum vertical-downwards displacements occurring near the penetrometer sleeve (Figure 183c). A similar result was obtained by Jiang et al. [2006b]. On the contrary, in the zones 2 and 3 vertical displacements either decrease linearly (T163) or are kept almost constant with the VCC depth. Moreover, for test T164 the particles moved upward above the penetration depth \( h_p \) and downward below \( h_p \) (zones 2 and 3). For T16Rot test, the particle motion was always upward in zone 2 (Figure 185c), but downward above the penetration depth \( h_p \) and upward below \( h_p \) in the zone 3 (Figure 187c).
Figure 164: Macro response ($q_c$ vs. $h_p$) of the tests include in the micro analysis (a) effect of initial density, (b) effect of BC, (c) effect of $K_0$ and (d) effect of particle rotation.
Figure 165: Displacement field for T16: MediumIsoBC1 during (a)-(b) shallow penetration and (c)-(d) deep penetration.
Figure 166: Displacement field for T20: DenseIsoBC1 during (a)-(b) shallow penetration and (c)-(d) deep penetration
Figure 167: Displacement field for T163: DenseKoBC1 during (a)-(b) shallow penetration and (c)-(d) deep penetration.
Figure 168: Displacement field for T164: DenseKoBC3 during (a)-(b) shallow penetration and (c)-(d) deep penetration
Figure 169: Displacement field for T16Rot: MediumIsoRotBC1 during (a)-(b) shallow penetration and (c)-(d) deep penetration
Figure 170: Plan view of spheres colored to indicate magnitude of normalized displacement ($\frac{\Delta z}{d_{c}}$) in z-direction for shallow penetration for $T_{16}$: MediumIsoBC1; (a) xz-plane (Cut 1) (b) yz-plane (Cut 2) and $T_{20}$: DenseIsoBC1 (c) xz-plane (Cut 1), (d) yz-plane (Cut 2).
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Figure 171: Plan view of spheres colored to indicate magnitude of normalized displacement \( \frac{\Delta z}{d_c} \) in z-direction for shallow penetration for T163: DenseKoBC1; (a) xz-plane (Cut 1) (b) yz-plane (Cut 2) and T164: DenseKoBC3 (c) xz-plane (Cut 1), (d) yz-plane (Cut 2)

Figure 172: Plan view of spheres colored to indicate magnitude of normalized displacement \( \frac{\Delta z}{d_c} \) in z-direction for shallow penetration for T16Rot: MediumIsoRotBC1 (a) xz-plane (Cut 1), (b) yz-plane (Cut 2)
Figure 173: Plan view of spheres colored to indicate magnitude of normalized displacement $(\frac{\Delta z}{d_c})$ in z-direction for deep penetration for $T_{16}$: MediumIsoBC$_1$; (a) xz-plane (Cut 1) (b) yz-plane (Cut 2) and $T_{20}$: DenseIsoBC$_1$ (c) xz-plane (Cut 1), (d) yz-plane (Cut 2)
Figure 174: Plan view of spheres colored to indicate magnitude of normalized displacement ($\frac{\Delta z}{d_c}$) in z-direction for deep penetration for T163: DenseKoBC; (a) xz-plane (Cut 1) (b) yz-plane (Cut 2) and T164: DenseKoBC3 (c) xz-plane (Cut 1), (d) yz-plane (Cut 2)

Figure 175: Plan view of spheres colored to indicate magnitude of normalized displacement ($\frac{\Delta z}{d_c}$) in z-direction for deep penetration for T16Rot: MediumIsoRotBC1 (a) xz-plane (Cut 1), (b) yz-plane (Cut 2)
Figure 176: Plan view of spheres colored to indicate normalized magnitude of normalized total displacement (displ/d_c) for T16: MediumIsoBC1 and (a)-(b) shallow penetration and (c)-(d) deep penetration.
Figure 177: Plan view of spheres colored to indicate normalized magnitude of normalized total displacement for $T_{20}$: DenseIsoBC$_1$ (displ/$d_c$) and (a)-(b) shallow penetration and (c)-(d) deep penetration.
Figure 178: Plan view of spheres colored to indicate normalized magnitude of normalized total displacement (displ/\(d_c\)) for T163: DenseKoBC1 and (a)-(b) shallow penetration and (c)-(d) deep penetration.
Figure 179: Plan view of spheres colored to indicate normalized magnitude of normalized total displacement (displ/d_c) for T164: DenseKoBC3 and (a)-(b) shallow penetration and (c)-(d) deep penetration.
Figure 180: Plan view of spheres colored to indicate normalized magnitude of normalized total displacement ($\text{displ}/d_c$) for $T_{16}\text{Rot}$: MediumIsoRotBC1 and (a)-(b) shallow penetration and (c)-(d) deep penetration.

Figure 181: Zone of averaging displacement.
Figure 182: Incremental averaged displacements measured in x-, y-, z-direction in Zone 1 during shallow penetration.
Figure 183: Incremental averaged displacements measured in x-, y-, z-direction in Zone 1 during deep penetration
Figure 184: Incremental averaged displacements measured in x-, y-, z-direction in Zone 2 during shallow penetration.
Figure 185: Incremental displacements measured in x-, y-, z-direction in Zone 2 during deep penetration
Figure 186: Incremental displacements measured in x-, y-, z-direction in Zone 3 during shallow penetration
Figure 187: Incremental displacements measured in x-, y-, z-direction in the Zone 3 during deep penetration.
8.3 CONTACT FORCE ANALYSIS

8.3.1 Normal contact force network

The distribution of particle normal contact forces (CF) is obtained for xz- and yz-planes (Cut 1 and Cut 2) at two penetration stages namely shallow penetration (Case 1) and deep penetration (Case 2). The contact forces are segregated in three distinct levels: extreme (5 standard deviations above the mean); large (above average but not extreme); small (below average). The extreme forces are plotted in black, large in grey and small in light grey (figures 188-192).

8.3.1.1 Case 1: shallow penetration

In the shallow penetration case, the CPT has a great influence on the zone close to the penetrometer, located just above and below the tip. This zone is characterized by a large magnitude of CF. The size of the zone of influence, primary, depends on the initial conditions of the granular assembly (stress state, relative density and boundary conditions). Hence, it is expected that larger CF will be observed for tests with higher confining stresses and density and will result in larger $q_c$. What is more interesting is that the characteristic CF concentrations close to the cone tip were not observed for a case with free particle rotation (T16Rot). This can be seen in Figure 192a and Figure 192b. It is also observed that boundary conditions have an important influence on the contact force development. So, for the T164 test performed under BC3 3 boundary conditions, the zone with higher CF was much wider and had higher CF than in the tests (T16, T20, T163) performed under BC1 4 boundary conditions. This is in agreement with the BC3 boundary conditions resulted in a higher $q_c$ at shallow penetration. Higher confining vertical stress (going from T20 to T163) has a small effect in the force pattern.

8.3.1.2 Case 2: deep penetration

In deep penetration, the CFs concentration is observed mostly close to the cone tip except for test T164 where they also appear close to the sleeve. In all numerical tests performed under BC1 boundary conditions, a loss of above average contact forces is observed close to the cone shaft. Moreover, for BC1 the CF trace a pattern similar to the failure mechanisms shown in Figure 2.3 (chapter 2). Moreover the difference between BC1 and BC3 is that in the former, the contact forces create chains mostly oriented vertically while in the latter, the CF chains are oriented horizontally. Similar to shallow penetration case, test T16Rot with free particle rotation behaved completely different from the other tests. Once again, in this case no CF localization was observed.

8.3.2 Contacts and normal contact force orientations

The distribution of contact normal orientations viz. angles $\alpha_n$ and $\beta_n$ are presented for zone 1 during shallow and deep penetration. The $\alpha_n$ and $\beta_n$ are classified in $10^\circ$ bins. The number of contacts in a given direction is indicated by the radius magnitude

3 BC3: $\sigma_v=const.$ and $\epsilon_h=0$
4 BC1: $\sigma_v=const.$ and $\sigma_h=const.$
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Figure 188: Section with contact forces network for T16: MediumIso1 and (a)-(b) shallow penetration and (c)-(c) deep penetration

in the polar plot. Figure 193 and Figure 194 shows the polar diagrams of the angle \( \alpha^n \) as well as the number of contacts in the respective direction for layers 1 and 4. Figure 195 and Figure 196 show the polar diagrams of the angle \( \beta^n \) as well as the number of contacts in the respective direction for layers 1 and 4.

8.3.2.1 \( \alpha^n \)-orientation

In shallow (Figure 193: blue line) and deep penetration (Figure 194: red line), a favored \( \alpha^n \) orientation is not observed and the number of contacts of different \( \alpha \) seems to oscillate around a constant value. However, for a given \( \alpha \) orientation, the number of contacts is varying depending on the overall loss or gain of particle contacts. The \( \alpha \)-orientation is more uniform in layer 1 (shallow penetration) but less uniform (with peaks and troughs) in layer 4 (particularly after deep penetration). In general the number of contacts reduced with penetration for all tests, except for T16Rot.

8.3.2.2 \( \beta^n \)-orientation

Looking at the \( \beta^n \) distribution of normal contact forces in layer 1 (Figure 195) but during deep penetration (Figure 196) we observe that most of the CFs are oriented in the range \(-40^\circ \pm 10 \text{ (320^\circ in the figure)} \) to \(30^\circ \pm 10\), that is perpendicular to the cone tip (\( \pm 30^\circ \)) and to the shaft (0^\circ). Moreover, in the layer 1 the deep penetration enforced the principal direction of contact forces to be horizontal. Similar to \( \alpha \)-orientation, the number of contacts with a given angle reduces with VCC depth.
8.3 Contact Force Analysis

Figure 189: Section with contact forces network for T20: DenseIsoBC1 and (a)-(b) shallow penetration and (c)-(c) deep penetration

8.3.3 Histograms of normal contact force in the vertical (xz) plane

Figure 197 and Figure 198 show the histograms of contact normal force magnitude in xz-plane measured in zone 1 and layer 1 for shallow penetration and in zone 1 and layer 4 for deep penetration. Looking at the figures we observe significant increment of the magnitude of the contact forces and rotations close to the cone (comparing to the initial state: Chapter 6). Moreover, it can be observed that important differences between DEM material deposited under anisotropic and isotropic conditions at initial state are not visible during cone penetration. The large contact forces are perpendicular to the cone tip.
Figure 190: Section with contact forces network for T163: DenseKoBC1 and (a)-(b) shallow penetration and (c)-(c) deep penetration
Figure 191: Section with contact forces network for T164: BenseKoBC3 and (a)-(b) shallow penetration and (c)-(c) deep penetration
Figure 192: Section with contact forces network for T16Rot: MediumIsoRotBC1 and (a)-(b) shallow penetration and (c)-(c) deep penetration
Figure 193: Contact normal orientation $\alpha^n$ measured in zone 1 and layer 1.

(black color: initial stage (before CPT), blue color: shallow penetration ($\frac{z-H_{cc}}{d_c} = -1.4$) and red color: deep penetration ($\frac{z-H_{cc}}{d_c} = -5.6$))
Figure 194: Contact normal orientation $\alpha_n$ measured in zone 1 and layer 4.

(black color: initial stage (before CPT), blue color: shallow penetration ($\frac{z-H_{ Ness}}{d_c} = -1.4$) and red color: deep penetration ($\frac{z-H_{ Ness}}{d_c} = -5.6$))
Figure 195: Contact normal orientation $\beta^m$ measured in zone 1 and layer 1.

(black color: initial stage (before CPT), blue color: shallow penetration ($\frac{z-H_{czz}}{d_z} = -1.4$) and red color: deep penetration ($\frac{z-H_{czz}}{d_z} = -5.6$))
The micro response of VCC CPT models

(a) T16, MediumIsoBC1, $\beta$
(b) T20, DenseIsoBC1, $\beta$
(c) T163, DenseKoBC1, $\beta$
(d) T164, DenseKoBC3, $\beta$
(e) T16Rot, MediumIsoRotBC1, $\beta$

Figure 196: Contact normal orientation $\beta^m$ measured in zone 1 and layer 4.

(black color: initial stage (before CPT), blue color: shallow penetration ($\frac{z-H_{vcc}}{d_c} = -1.4$) and red color: deep penetration ($\frac{z-H_{vcc}}{d_c} = -5.6$))
Figure 197: Contact normal force magnitude in xz-plane measured in zone 1 and layer 1 for shallow penetration
Figure 198: Contact normal force magnitude in xz-plane measured in zone 1 and layer 4 for deep penetration
8.4 Stress Analysis

8.4.1 Stress Field around Cone

Figures 199-206 provide the contour plots of normalized stresses ($\frac{\sigma_{xx}}{\sigma_0}$) in a $xz$-plane section and for four different cases: (1) $D_R$ varies: $T_{16}$ and $T_{20}$, (2) BC varies (BC1/BC3): $T_{163}$ and $T_{164}$, (3) initial loading paths varies (Iso/$K_0$): $T_{20}$ and $T_{163}$ and (4) particle rotation varies (inhibited/free): $T_{16}$ and $T_{16}\text{Rot}$. The contour plots are generated by interpolation of particles stresses on a uniform grid. The grid was used later here for strain calculation (described in Chapter 4 (Section 4.4.2.3)).

8.4.1.1 Case 1: Shallow Penetration

In all cases (1-4) the CPT had a large influence on granular assembly that led to large stress concentrations in the vicinity of the cone tip. The magnitude of $\sigma_z$ is much higher than the other components. A similar pattern is observed for $\sigma_r$, $\sigma_\theta$ and $\sigma_z$ in all cases with restricted particle rotations and under BC1 boundary conditions ($T_{16}$, $T_{20}$, $T_{163}$). Moreover, in those cases the size of the zone affected by penetration is found to depend very little on the initial conditions of the material and is around (1-2)$d_c$ in the $z$-direction and $\approx 3d_c$ in the $r$-direction for initial $\sigma_r$ and $\sigma_\theta$. Meanwhile for $\sigma_z$ the zone with higher increase of stress is more vertically directed. For the test under BC3 boundary conditions ($T_{164}$), the zone influenced by CPT is larger ($2d_c$ in the $z$-direction and $4d_c$ in the radial direction). The stress distribution for test with enabled particle rotation ($T_{16}\text{Rot}$) is completely different from those of the former cases. In $T_{16}\text{Rot}$ no stress localization close to the cone tip is observed. The stresses during CPT remain much closer to the initial values (only local increase in stresses was observed with no characteristic pattern).

8.4.1.2 Case 2: Deep Penetration

Once again, a similar pattern is observed for the stresses in the tests: $T_{16}$, $T_{20}$ and $T_{163}$ (under BC1). For deep penetration case, an important stress concentration is observed close to the cone tip but not close to the sleeve. This is in agreement with the low shaft resistance (Chapter 7). Important differences are observed in the numerical simulations for test $T_{164}$ (under BC3) and $T_{15}\text{Rot}$ (with free particle rotations). In the former, much higher changes in stresses are observed (in radial direction-$\sigma_r$, $z$-direction-$\sigma_\theta$ and $\sigma_\theta$ around cone and shaft), whereas in the latter much smaller stress changes are noted.
Figure 199: Contour plot of normalized stresses ($\frac{\sigma_{ii}}{\sigma_0}$) for shallow penetration. Medium dense (T16: MediumIsoBC1) vs. dense (T20: DenseIsoBC1) material.
Figure 200: Contour plot of normalized stresses \( \frac{\sigma_{ii}}{p_c} \) for deep penetration. Medium dense (T16: MediumIsoBC1) vs. dense (T20: DenseIsoBC1) material.
Figure 201: Contour plot (note different scale) of normalized stresses $\left(\frac{\sigma_{ij}}{\sigma_0}\right)$ for shallow penetration. BC1 (T163: DenseKoBC1) vs. BC3 (T164: DenseKoBC3).
Figure 202: Contour plot (note different scale) of normalized stresses ($\frac{\sigma_{ij}}{\sigma_{10}}$) for deep penetration. BC1 (T163: DenseKoBC1) vs. BC3 (T164: DenseKoBC3).
Figure 203: Contour plot of normalized stresses ($\frac{\sigma_{ii}}{\sigma_0}$) for shallow penetration. Isotropic (T20) vs. anisotropic (T163) consolidation (to similar horizontal stress).
Figure 204: Contour plot (note different scale) of normalized stresses ($\frac{\sigma_{ii}}{\sigma_{00}}$) for deep penetration. Isotropic (T20) vs. anisotropic (T163) consolidation (to similar horizontal stress).
Figure 205: Contour plot (note different scale) of normalized stresses ($\frac{\sigma_{ij}}{p_0}$) for shallow penetration. Particle rotation inhibited (T16) vs. particle rotation allowed (T16Rot).
Figure 206: Contour plot (note different scale) of normalized stresses ($\sigma_n / \sigma_0$) for deep penetration. Particle rotation inhibited (T16) vs. particle rotation allowed (T16Rot).
8.4.2 Stress distribution and loading paths

Figures 207-214 show the distribution of the normalized stress ($\sigma_r$, $\sigma_\theta$, $\sigma_z$) calculated in zones 1-3. The selected zones are cylindrical shells which trace on a plane section is shown in Figure 199a. It can be seen that peak values of stresses are observed at the position of cone tip in zone 1 (close to the cone). In addition, the magnitude of stresses decrease with distance from the cone. Moreover, for all tests the pattern was similar, except for T16Rot. Next to the cone (zone 1), during shallow penetration, the stresses below the cone tip tend to their initial value in all cases. In deep penetration, the stresses increased with $\frac{z-h_{lev}}{d_c}$ from their initial value to a large peak stress (near the cone tip) and then decrease above the tip to a constant value which is larger than the corresponding initial values. Similar behavior was observed by Jiang et al. [2006b] in 2D. Moreover, the choice of boundary conditions (BC) is found to have an important influence on the evolution of the stresses with VCC depth. Hence, BC3 led to larger peak stresses due to a lack of boundary constraint on the stress value (stresses can develop freely). The maximum $\sigma_r$, $\sigma_\theta$ and $\sigma_z$ calculated during deep penetration for T164 were approximately 100, 40 and 30 times larger than the initial mean stress, respectively. The lowest increase in the stresses during deep penetration is observed for T16Rot (free particle rotation). Table 32 collects the peak stress values detected for all cases in Zone 1. It not always the case that stresses are higher at deep penetration than at shallow penetration. The different stress components in peaks have a similar order of magnitude. In the BC1 cases the peak is always below 55p0, whereas for the BC3 case reaches up to 83p0. The case with rotation shows very small increases.

Figure 216 shows the pq stress paths during CPT observed at several measurement points (Figure 215). In addition, the peak and residual strength envelopes of the granular material obtained from triaxial compression tests are also drawn in the figure. It can be observed that during CPT the discrete assemblies undergo an evident loading and unloading process. Moreover, the stress state arrive slightly over the triaxial compression peak strength envelope in all cases and specially in the zones close to the symmetry line. A possible explanation for this fact is the enhanced role of dilatancy in the constrained environment of the VCC.

<table>
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8.4.3 Orientation/rotation of the maximum principal stress, $\sigma_1$

Figure 217–Figure 221 present the orientation of the maximum principal stress ($\sigma_1$) observed at three penetration stages, viz. initial, shallow penetration and deep penetration. These figures show that the soil in all cases and different positions undergoes an evident rotation of principal stress between stages. It was observed that for shallow penetration and in the zone situated just below the cone tip the orientation of $\sigma_1$ was close to vertical (except T16Rot). For deep penetration, the orientation of $\sigma_1$ was vertical just below the cone tip and horizontal in the zone far from it (except T163). The closer to the cone device and/or ground surface, the larger is the maximum rotation. Moreover, the $\sigma_1$ principal direction was also dependent on the initial stress and boundary conditions. Hence, for all tests prepared under isotropic conditions the initial orientation of $\sigma_1$ was random (with horizontal orientation in the center of specimen and vertical close to radial wall), while for tests prepared under 1D-consolidation the orientation of $\sigma_1$ was vertical in all samples. The boundary type conditions were found to play an important effect on the orientation of $\sigma_1$. 
Figure 207: Normalized stresses calculated in the Zone 1 (next to the cone), 2 (in the middle between cone and the radial wall), 3 (next to the radial wall) for shallow penetration. Medium dense (T16) vs. dense (T20) material.

dashed bold line defines the position of the cone tip
Figure 208: Normalized stresses calculated in the Zone 1 (next to the cone), 2 (in the middle between cone and the radial wall), 3 (next to the radial wall) for deep penetration. Medium dense (T16) vs. dense (T20) material.

dashed bold line defines the position of the cone tip
Figure 209: Normalized stresses calculated in the Zone 1 (next to the cone), 2 (in the middle between cone and the radial wall), 3 (next to the radial wall) for shallow penetration. BC1 (T163) vs. BC3 (T164).

dashed bold line defines the position of the cone tip
Figure 210: Normalized stresses calculated in the Zone 1 (next to the cone), 2 (in the middle between cone and the radial wall), 3 (next to the radial wall) for deep penetration. BC1 (T163) vs. BC3 (T164).

dashed bold line defines the position of the cone tip
Figure 211: Normalized stresses calculated in the Zone 1 (next to the cone), 2 (in the middle between cone and the radial wall), 3 (next to the radial wall) for shallow penetration. Isotropic (T20) vs. anisotropic (T163) consolidation (to similar horizontal stress).

dashed bold line defines the position of the cone tip
8.4 Stress Analysis

Figure 212: Normalized stresses calculated in the Zone 1 (next to the cone), 2 (in the middle between cone and the radial wall), 3 (next to the radial wall) for deep penetration. Isotropic (T20) vs. anisotropic (T163) consolidation (to similar horizontal stress).

dashed bold line defines the position of the cone tip
Figure 213: Normalized stresses calculated in the Zone 1 (next to the cone), 2 (in the middle between cone and the radial wall), 3 (next to the radial wall) for shallow penetration. Particle rotation inhibited (T16) vs. particle rotation allowed (T16Rot).

dashed bold line defines the position of the cone tip
Figure 214: Normalized stresses calculated in the Zone 1 (next to the cone), 2 (in the middle between cone and the radial wall), 3 (next to the radial wall) for deep penetration. Particle rotation inhibited (T16) vs. particle rotation allowed (T16Rot).

dashed bold line defines the position of the cone tip
Figure 215: Position of the grid points to observe loading path for different position of cone tip ($h_p = 0.1 - 0.5$ m)
Figure 216: Loading path observed at the five different zones for different cone positions: red dashed line: triaxial critical state envelope, black dashed line: triaxial peak envelope
Figure 217: Stream plots of the maximum principal stress orientation during initial stage, shallow and deep penetration for T16
Figure 218: Stream plots of the maximum principal stress orientation during initial stage, shallow and deep penetration for T20
Figure 219: Stream plots of the maximum principal stress orientation during initial stage, shallow and deep penetration for T163.
Figure 220: Stream plots of the maximum principal stress orientation during initial stage, shallow and deep penetration for T164
Figure 221: Stream plots of the maximum principal stress orientation during initial stage, shallow and deep penetration for T16Rot
8.5 STRAIN FIELD AROUND THE CONE

The strain calculation method used here the non-local meshfree interpolation approach for strain calculation proposed by O’Sullivan et al. [2003]. An overview of this method is given in Chapter 4. The calculation of radial and circumferential strains required some adaptations, presented in Appendix D. The sign convention in the plots of $\varepsilon_r$, $\varepsilon_\theta$ and $\varepsilon_z$ is negative for compression and positive for extension. In the volumetric plots ($\varepsilon_{vol}$) the sign for compression is positive.

8.5.1 Contour plots

The contour plots of $\varepsilon_r$, $\varepsilon_\theta$, $\varepsilon_z$ in xz-, yz- and xy-plane for shallow and deep penetrations are shown in Figure 222-231. The strain fields resulting from the meshfree interpolation functions offer a meaningful smoothed representation of the displacement fields. The volumetric behavior is shown in Figure 232-236.

8.5.1.1 Case 1: shallow penetration

It appears clear from the Figure 222-Figure 226 that the strains $\varepsilon_r$ and $\varepsilon_\theta$ and $\varepsilon_z$ in xz-plane are quite similar (small differences) to $\varepsilon_r$ and $\varepsilon_\theta$ and $\varepsilon_z$ in yz-plane. Hence, the strain representation quickly reveals the axisymmetric behavior of the system. High strain concentration is observed close to the cone tip ($\varepsilon_r$ and $\varepsilon_\theta$) and just below it ($\varepsilon_z$) and the pattern seems to be unaffected by the test-conditions (except for test with free particle rotations: MediumIsoRotBc1). Looking at $\varepsilon_r$ we observe contraction behavior on both sides of the cone device and expansion in the region directly below the cone tip. On the other hand, in the contour plots of $\varepsilon_z$ we observe important contraction zone just below the cone tip.

The zones close to the bottom and radial walls show a negligible effect of the penetrating cone. The volumetric behavior is shown on Figure 232(a-b)-Figure 236(a-b). The observed contraction is due to the movements of spheres below the cone base. The magnitude of volumetric and shear strains in this phase are similar in all cases. Shear strains extend further apart from the cone than the volumetric strains.

8.5.1.2 Case 2: deep penetration

During deep penetration (Figure 227-Figure 231), the strain pattern is similar in all the cases and $\varepsilon_r$, $\varepsilon_\theta$ in xz-plane are similar to $\varepsilon_r$, $\varepsilon_\theta$ in yz-plane, respectively. The strain magnitudes and the volume affected by them are higher than during shallow penetration. Deformation in the radial direction shows contraction within the region around the cone and expansion in the region directly below the cone tip. In the $\varepsilon_r$ contour plot we observe a similar trend as observed earlier for shallow penetration; soil mass close to the cone tip and shaft expand, while zones on both sides of the cone contract. A positive $\varepsilon_z$ is observed on the surface close to the shaft (contraction) while negative (dilation) close to the cone tip and on both sides of it. The pattern of shear and volumetric strains shows again a large extend of the zone affected by shear.
Figure 22: Strain field for T16 (MediumIsoBC) during shallow penetration

The sign convention in the plots of $\epsilon_r$, $\epsilon_\theta$, and $\epsilon_z$ is negative for compression and positive for extension. In the volumetric plots ($\epsilon_{vol}$) the sign for compression is positive.
Figure 223: Strain field for T2o (DenseIsoBC1) during shallow penetration

The sign convention in the plots of $\epsilon_r$, $\epsilon_0$ and $\epsilon_z$ is negative for compression and positive for extension. In the volumetric plots ($\epsilon_{vol}$) the sign for compression is positive.
(a) $\epsilon_r$, xz-plane
(b) $\epsilon_r$, yz-plane
(c) $\epsilon_r$, xy-plane, just beneath cone tip

(d) $\epsilon_\theta$, xz-plane
(e) $\epsilon_\theta$, yz-plane
(f) $\epsilon_\theta$, xy-plane, just beneath cone tip

(g) $\epsilon_z$, xz-plane
(h) $\epsilon_z$, yz-plane
(i) $\epsilon_z$, xy-plane, just beneath cone tip

Figure 224: Strain field for T163 (DenseKoBC1) during shallow penetration

The sign convention in the plots of $\epsilon_r$, $\epsilon_\theta$ and $\epsilon_z$ is negative for compression and positive for extension. In the volumetric plots ($\epsilon_{vol}$) the sign for compression is positive.
Figure 225: Strain field for T164 (DenseKoBC3) during shallow penetration
   The sign convention in the plots of $\epsilon_r$, $\epsilon_\theta$ and $\epsilon_z$ is negative for compression and positive for extension. In the volumetric plots ($\epsilon_{vol}$) the sign for compression is positive.
Figure 226: Strain field for T\textsubscript{16Rot} (MediumIsoRotBC1) during shallow penetration.

The sign convention in the plots of $\epsilon_r$, $\epsilon_\theta$ and $\epsilon_z$ is negative for compression and positive for extension. In the volumetric plots ($\epsilon_{vol}$) the sign for compression is positive.
The sign convention in the plots of $\epsilon_{r}$, $\epsilon_{\theta}$ and $\epsilon_{z}$ is negative for compression and positive for extension. In the volumetric plots ($\epsilon_{vol}$) the sign for compression is positive.
Figure 228: Strain field for T20 (DensIsoBC1) during deep penetration

The sign convention in the plots of $\epsilon_r$, $\epsilon_\theta$ and $\epsilon_z$ is negative for compression and positive for extension. In the volumetric plots ($\epsilon_{vol}$) the sign for compression is positive.
Figure 229: Strain field for T163 (DenseKoBC1) during deep penetration

The sign convention in the plots of $\epsilon_r$, $\epsilon_\theta$ and $\epsilon_z$ is negative for compression and positive for extension. In the volumetric plots ($\epsilon_{\text{vol}}$) the sign for compression is positive.
Figure 230: Strain field for T164 (DenseKoBC3) during deep penetration
The sign convention in the plots of $\varepsilon_r$, $\varepsilon_\theta$ and $\varepsilon_z$ is negative for compression and positive for extension. In the volumetric plots ($\varepsilon_{vol}$) the sign for compression is positive.
Figure 231: Strain field for T16Rot (MediumIsoRotBC1) during shallow penetration

The sign convention in the plots of $\epsilon_r$, $\epsilon_\theta$ and $\epsilon_z$ is negative for compression and positive for extension. In the volumetric plots ($\epsilon_{vol}$) the sign for compression is positive.
Figure 232: Volumetric and distortional strain fields for T16 (MediumIsoBC1) during shallow and deep penetration
The sign convention in the plots of $\epsilon_r$, $\epsilon_\theta$ and $\epsilon_z$ is negative for compression and positive for extension. In the volumetric plots ($\epsilon_{vol}$) the sign for compression is positive.
Figure 233: Volumetric and distortional strain field for T20 (DenseIsoBC1) during shallow and deep penetration

The sign convention in the plots of $\epsilon_r$, $\epsilon_\theta$ and $\epsilon_z$ is negative for compression and positive for extension. In the volumetric plots ($\varepsilon_{\text{vol}}$) the sign for compression is positive.
Figure 234: Volumetric and distortional strain field for $T_{163}$ (DenseKoBC1) during shallow and deep penetration

The sign convention in the plots of $\epsilon_r$, $\epsilon_\theta$ and $\epsilon_z$ is negative for compression and positive for extension. In the volumetric plots ($\epsilon_{vol}$) the sign for compression is positive.
Figure 235: Volumetric and distortional strain field for T164 (DenseKoBC) during shallow and deep penetration.

The sign convention in the plots of $\varepsilon_r$, $\varepsilon_\theta$ and $\varepsilon_z$ is negative for compression and positive for extension. In the volumetric plots ($\varepsilon_{\text{vol}}$) the sign for compression is positive.
Figure 236: Volumetric and distortional strain field for T16r (MediumIsoRotBC1) during shallow and deep penetration
The sign convention in the plots of $\epsilon_r$, $\epsilon_\theta$ and $\epsilon_z$ is negative for compression and positive for extension. In the volumetric plots ($\epsilon_{vol}$) the sign for compression is positive
8.5.2 Strain paths

Figure 215 shows five zones (grid points, described in detail in chapter 4) that were chosen to track the soil mass deformations while the penetration proceeds. Figure 237 to Figure 239 present the evolution of $\epsilon_r$, $\epsilon_\theta$, $\epsilon_z$ with normalized penetration depth ($h_p$ is a position of the cone tip, $z_{GP}$ is vertical position of the considered grid point, $H_{VCC}$ height of VCC and $d_c$ diameter of the cone). A negative value of normalized penetration depth indicates that the cone tip did not reach the depth of the considered grid point, while a positive value means that the cone tip has already passed the depth of the considered grid point.

Figure 237 shows the deformations in $z$ direction showing insignificant (T16, T20, T16Rot) or small (T163, T164) effect on the zones positioned close to the radial wall (GP3) and at half distance between cone and radial wall (GP4). The grid point located at the bottom of the VCC below the cone is showing continuous contraction during the penetration process. At both sides of the cone we observe contraction at the initial stage of penetration (cone tip located above the points) and after the cone tip crossed the grid depth the soil undergoes dilation. A maximum dilation of around 12% was observed for medium isotropically compressed sample (T16).

Moreover, it can be observed that two zones, GP1 and GP2, laying at the same level (the same distance from the axis) but on different sides (left and right) of the cone confirm the axisymmetric behavior of the system.

Figure 238 shows the deformations in $r$ direction showing a small effect on the grid points located close to the radial wall (GP3) and in the half distance between cone and radial wall (GP4). The penetrating cone cause the soil at the bottom of VCC to expand (except for the sample with free particle rotation: Figure 238e). The selected grid points (GP1 and GP2) located on both sides of the cone shows (i) extension at the initial penetration depths (below the cone) and compression above the cone (MediumIsoBC1: Figure 238a), (ii) only extension during complete penetration (DenseIsoBC1: Figure 238b, DenseKoBC1: Figure 238c and DenseKoBC3: Figure 238d) and (iii) extension (right grid point) and compression (left grid point) during full penetration process (MediumIsoRotBC1: Figure 238e). The axisymmetric behavior observed in $\epsilon_z$ was not so clear while looking at the $\epsilon_r$.

The circumferential strains ($\epsilon_\theta$) presented on Figure 239 show again small effect on the zones located far from the cone device and large increase in strain values close to it ($\approx 16\%$ for test performed under BC3 boundary conditions). It can be observed that after the cone passes the observation point depth $\epsilon_\theta$ reaches a steady state (except for the sample with free particle rotations, where after a peak the reduction in strain is observed).

The volumetric strains ($\epsilon_v$) presented in Figure 240 and distortional strains (Figure 241) show contraction behavior. Similar to previous strains components the zones less affected by penetration process are those close to the radial wall (GP4) and at the bottom of the VCC (GP5).
Figure 237: Vertical strain evolution at given grid points (GP) for different penetration depths. The sign convention in the plots of $\epsilon_r$, $\epsilon_\theta$ and $\epsilon_z$ is negative for compression and positive for extension. In the volumetric plots ($\epsilon_{vol}$) the sign for compression is positive.
Figure 238: Radial strain evolution at given grid points (GP) for different penetration depths. The sign convention in the plots of $\epsilon_r$, $\epsilon_\theta$ and $\epsilon_z$ is negative for compression and positive for extension. In the volumetric plots ($\epsilon_{vol}$) the sign for compression is positive.
Figure 239: Circumferential strain evolution at given grid points (GP) for different penetration depths. The sign convention in the plots of $\epsilon_r$, $\epsilon_\theta$ and $\epsilon_z$ is negative for compression and positive for extension. In the volumetric plots ($\epsilon_{vol}$) the sign for compression is positive.
Figure 240: Volumetric strain evolution at given grid points (GP) for different penetration depths.
The sign convention in the plots of $\varepsilon_r$, $\varepsilon_\theta$ and $\varepsilon_z$ is negative for compression and positive for extension. In the volumetric plots ($\varepsilon_{vol}$) the sign for compression is positive.
Figure 241: Distortional strain evolution at given grid points (GP) for different penetration depths
The sign convention in the plots of $\varepsilon_r$, $\varepsilon_\theta$ and $\varepsilon_z$ is negative for compression and positive for extension. In the volumetric plots ($\varepsilon_{vol}$) the sign for compression is positive.
8.6 **Summary**

In this chapter we examined the micro-and meso-response of the VCC during cone penetration in a 3D discrete granular material. The main conclusions are:

1. the CPT causes the soil close to the cone device to move in a very complex manner. During penetration process the soil near the penetrometer is pushed sideways and downward to create a space for the penetrating cone. Moreover, during shallow penetration, the soil close to the surface may move upward. The boundary and initial conditions of the specimen are found to have an important influence on the displacement paths. Hence, CPTs performed under BC1 and BC3 boundary conditions will displace in a completely different manner. Moreover, free particle rotation will cause different displacement paths than the tests with restricted particle rotation.

2. The penetration process leads to high concentration of contact forces close to the cone tip (except for tests with free particle rotation) and close to the shaft, as well. The orientation of normal contact forces also changes during penetration and these changes are more pronounced in the zones close the cone. Moreover, for a given orientation, the number of contacts is varying depending on the loss or gain of particle contacts.

3. The CPT causes the soil close to the cone to undergo an evident loading and unloading process. During CPT, the stresses close to the cone tip increase from their initial value to the large peak stress, and then decrease to a constant value (slightly larger than the initial value). The stresses decrease with increasing distance from the cone. Close to the shaft a large concentration of stresses is not observed, except for T164 performed under BC3 boundary conditions. The choice of boundary conditions (BC) is found to have an important influence on the evolution of the stresses with VCC depth. BC3 leads to larger peak stresses due to a lack of boundary constrains (stresses can develop freely).

4. The soil penetrated by the cone undergo an evident rotation of principal stresses which can be larger than 180°. This rotation of principal stresses is influenced by initial stress state and boundary conditions.

5. The strain fields resulting from the novel meshfree interpolation functions offer a meaningful smoothed representation of the displacement fields. The strain contour plots reveal the axisymmetric behavior of the system.