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Application of Geo-contact to pile installation using the CPDI variant of Material Point Method (MPM)

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ABSTRACT

The Material Point Method (MPM), a mesh-based particle method, has been developed to mitigate the mesh distortion problem observed in the Finite Element Method (FEM) when simulating large deformation processes. A modified version of MPM – the Convected Particle Domain Interpolation (CPDI) method –has enhanced the reliability of predictions. Nevertheless, the modelling of the interaction between the bodies remains challenging due to the lack of well-defined surfaces. For the simulationof the installation of a pile, the interaction between soil and structure plays an important role during an analysis. The Geo-contact algorithmpresented in this paper provides a robust algorithm that actively detects contacts, develops contact forces and reacts according to the physical behaviour. Using this approach, a pile installation simulation is performed to demonstrate the capability of CPDI to model penetration problems involving large deformation.

KEY WORDS: MPM; CPDI; soil-structure interaction; pile installation; saturated sand.

INTRODUCTION

Piles are often used to support large structures. The assessment of a pile with regard to its efficiency requires considerable effort given that varying soil conditions, installation method, dimensions and effects of installation on the soil influence the performance of a pile. In the early days, the installation process was studied through one-dimensional analysis considering spring and dashpot systems for the soil. This provided basic information but not the real physical effects that develop in a pile during installation. To extract such information, scaled model tests and full-scale experiments have been performed at additional cost. Numerical simulation has also been adopted to obtain information on soil-pile interaction processes, as well as on installation methods. Using axially-symmetric and three dimensional analyses, stress waves can be captured along with the resistance from the soil (Mabsout &Tassoulas, 1994). This contributes to reducing the cost and time for designing a better pile foundation for specific applications.

The installation of a pile is a dynamic process involving interaction between the pile and soil, together with large deformation in the soil that develops as it is displaced. MPM is considered for its ability to model large deformation better than the other approaches for simulating this complex process. Although this approach mitigates mesh distortion problems, difficulties arise in modelling the interaction between the bodies given that there is no clear boundary to define the interface between the soil and pile, thus making it challenging to detect and clearly define the soil-structure contact forces. To add to the challenges, it may also be necessary to include the influence of groundwater. Furthermore, as is typical in soil-structure interaction, the friction between the soil and structure should also be modelled, which requires implementing a robust contact algorithm. The frictional contact algorithm (FCA) developed by Bardenhagen & Kober (2004) serves the purpose in some applications. Contact detection is based on the nodal velocity projected from the contacting bodies. This creates a non-physical gap between the two bodies that depends on the coarseness of the computational mesh. Furthermore, their algorithm can introducenon-physical stress oscillations in the vicinity of the interface of two materials of different stiffness.

Thepenalty contact approach (PCA) by Hamad et al.(2017) considers linear elements to define the surface of a body. Each body is well defined and a penalty function governs the forces to be applied on the body. This formulation is similar to that used in the finite element theory as the linear elements behave similar to a finite element boundary. The master and slave elements are assigned based on the different stiffness of materials. By this, the oscillations of contact forces observed in frictional contact are eliminated. The contact definition is smooth and physical without any gap between the bodies. The main drawback of the penalty contact method is that it requires additional linear elements for the definition of boundaries. The computation cost is not affected much because the total number of particles for a body is considerably more than the number of linear elements. A further problem is that the boundaries must be predefined prior to the simulation. The contact regions should be estimated to identify interaction surfaces. This works well with solid bodies without damage or cracks but is difficult for geotechnical applications, in which a pile penetrating into a soil cannot have a predefined surface on both materials. Thus, the contact surface should be determined as the simulation progresses.

The Geo-contact algorithm (GCA)proposed by Ma et al. (2014) addresses the problems faced in the two previously described algorithms. Contact detection follows the frictional contact procedure, but the application of forces is through a penalty function to smoothen the interaction. This provides a robust algorithm for complex geotechnical simulations. The formulation for GCA is briefly discussed next. Thereafter the simulation of pile installation using the Geo-contact is presented. Here, the boundary and initial conditions of the problem are given and the simulation procedure along with the results is compared to those of other contact algorithms. Finally, conclusions are drawn based on the validations and results.

GEO-CONTACT ALGORITHM

The contact algorithm consists of three stages. First, the particles in contact are detected through the velocity-based nodal approach. The unit normal vectors are then calculated and the condition for each contact node is checked. In the second stage, contact forces are determined based on the contacting conditions, *i.e.*, tangential and normal forces. Up to this stage, the frictional contact formulation from Bardenhagen & Kober (2004) is followed. Finally, the normal forces acting on the bodies are provided using the penalty function to smoothen the forces thereby allowing conditional penetration (Ma et al., 2014).

In the following two bodies A and B might be considered with respective masses m_A and m_B that make contact at node P, as shown in the Figure 1.

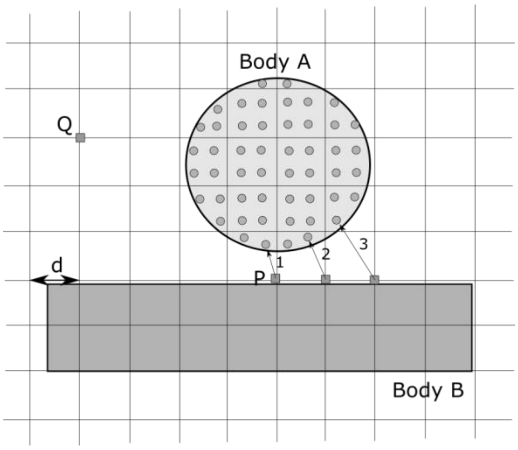

Figure 1 The contacting bodies and the penalty distance vectors at the contacting nodes

Step 1: Contact detection

After solving the governing equation to obtain nodal accelerations and nodal velocities (v_A and v_B), the combined velocity (v_c) is calculated from the equation,

$$v_c = \frac{m_A V_A + m_B V_B}{m_A + m_B} \tag{1}$$

The contacting particles are identified through the nodes which have velocity contribution from both the bodies. This is termed as the contact node (P).

To determine the contact node, first every nodal velocity contributed by body A (v_A) is compared with the combined velocity. If v_A is not equal to v_c, then it is a contact node.Consider another node Q, where there is no contribution from both the bodies. Here, the velocities v_A and v_c will be equal and zero; indicating non-contacting node. Also, the nodes inside the bodies will have both the velocities equal as there is no contribution from the other body. Further, velocity correction is made based on the conditions given in next steps. The entire process is repeated for the body B with velocity (v_B).

Step 2: Contact forces

After the detection of the contact node, the separation and approach of the bodies are determined using the condition,

$$(v_A - v_c) \cdot n_i > 0 \tag{2}$$

where, n_i is the outward surface normal at the contact node.

If the bodies are separating then no velocity correction is applied. If the two bodies are approaching, then the normal force is applied to avoid penetration of the bodies into each other.

Normal (v_n)and tangential (v_t) velocities are calculated at the contact nodes according to,

$$v_n = [(v_A - v_c) \cdot n_i]n_i \tag{3}$$

$$v_t = (v_A - v_c) - v_n \tag{4}$$

From the velocities and nodal mass (M_i), the normal (F_n) and tangential (F_t) forces are obtained via,

$$F_n = \frac{M_i}{\mathrm{d}t} v_n \tag{5}$$

$$F_t = \frac{M_i}{\mathrm{d}t} v_t \tag{6}$$

Here, dt is the time step. Then the maximum allowed tangential forces due to the friction are obtained based on the friction co-efficient (μ),

$$F_t^{\max} = \mu \, \|F_n\| \tag{7}$$

This limits the tangential forces and according to these forces, sliding or no sliding condition is determined. Finally, the velocity correction is applied to the contact nodal velocity.

Step 3: Penalty function

The contact algorithm is complete with the two stages described above, which detects the contact nodes and determines the applied necessary forces. This basic formulation however leads to oscillations because of the undefined surface in MPM. Particles representing the surface of the body have limitations with the quality of computational mesh. The oscillations can be reduced by using more and smaller particles, which in turn increases the computational cost. To eliminate oscillations, in the GCA, a penalty function is adopted to smoothen the normal forces. Basically, it allows for some penetration by a gradual application of the normal force according to the distance between stiffer particle and contact node. The corrected normal velocity is obtained by the equation,

$$v_n' = f_p v_n \tag{8}$$

where, f_p is the penalty function defined as,

$$f_p = 1 - \left(\frac{\min(s,d)}{d}\right)^k \tag{9}$$

Here(s) is the distance between the outer particle and the contact node, which determines the penalty value based on the cell size (d). The penalty power (k) controls the amount of interpenetration via the penalty function curve. Various power values are tested to obtain minimum possible penetration. From Figure 1, the vectors 1,2 and 3 give the following three cases:

$$Vector\ 1:\ s \rightarrow 0, f_p \rightarrow 1$$
$$Vector\ 2:\ s \rightarrow d, f_p \rightarrow 0$$
$$Vector\ 3:\ s > d, f_p = 0$$

SIMULATION

Problem description

The initial configuration of a pile installation system is shown in Figure 2. The soil and pile are modelled as axisymmetric domains, given the symmetric nature of the problem. The soil domain has a height of 10 m and a width of 5 m. The particles around the path of installation are refined in comparison to the other regions. A total of5600 particles are considered for the sand region and 1000 particles for the pile. A hypoplastic constitutive model is used for the sand using the properties of Lausitz sand as given in Table 1 (Herle & Gudehus, 1999). The hypoplastic model developed by von Wolffersdorff (1996) is a non-linear model where the state of the material is described by the stress and void ratio. An extension to accommodate small strain stiffness was proposed by Niemunis & Herle(1997). The solid pile is modelled as linear elastic with an elastic modulus, E=2.6 GPa, Poisson's ratio, $\upsilon = 0.3$ and density, $\rho = 8$ g/cm^3. The length of the pile is 5 m and the radius is 0.15 m.

Table 1 Hypoplastic parameters for the Lausitz sand.

φ [°]	h_s[MPa]	n	e_{d0}	e_{c0}	e_{i0}	α	β
33	1600	0.19	0.44	0.85	1.0	0.25	1.0

m_R	m_T	R	χ	β_r
5	2	10^{-4}	6	0.5

The bottom of the sand domain is modelled assuming full fixity, with the radial displacement along the shear-free vertical boundary on the right hand side being zero (roller boundary). A hammer load is applied via traction on the top of the pile as pulse load in order to simulate an impact driven installation process. Here the peak load is at 0.05 s in every interval.

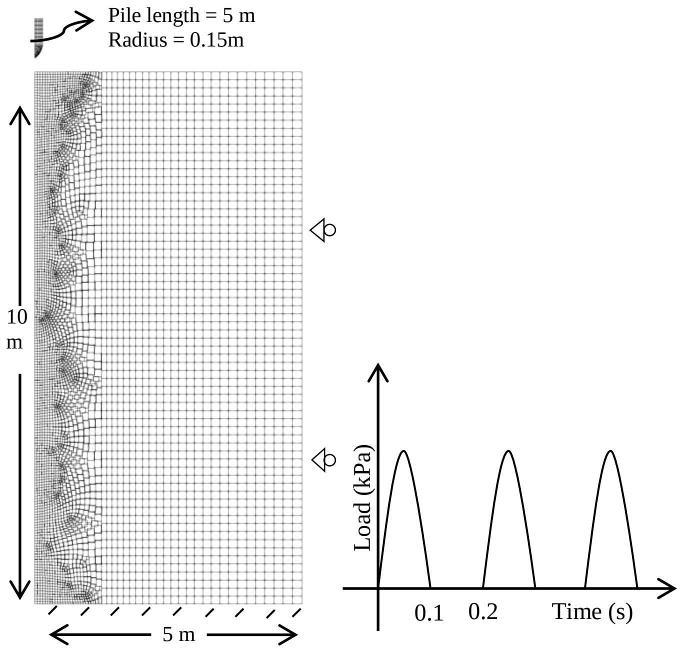

Figure 2 Initial configuration of the numerical model and the loading pattern for the installation of pile

The simulations are performed in two stages: firstly, a gravity load is applied to achieve the initial geostatic stresses in the sand and the pile is allowed to penetrate due to its self-weight. Thereafter, the cyclical hammering load of 1000 kPa amplitude (see Figure 2) is applied until the desired depth of installation is reached.

Results

This section compares the solutions from the Geo-contact analyses (GCA) with those by the frictional (FCA) and penalty (PCA) contact algorithms. In a first step the radial stress distributions and pile penetrations for GCA and FCA are compared in Figures 3 and 4, respectively.

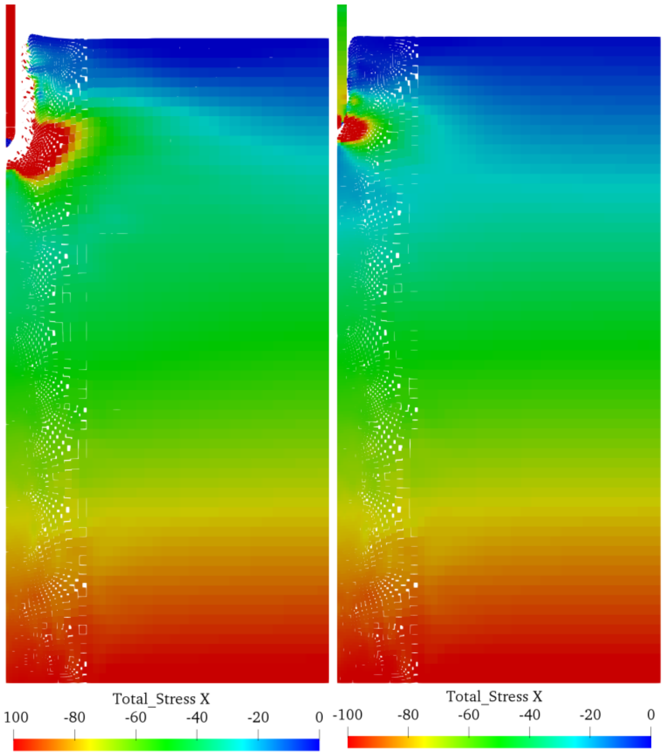

Figure 3 Radial stress distributions obtained by using FCA (left) and GCA (right) during an impact blow (in kPa)

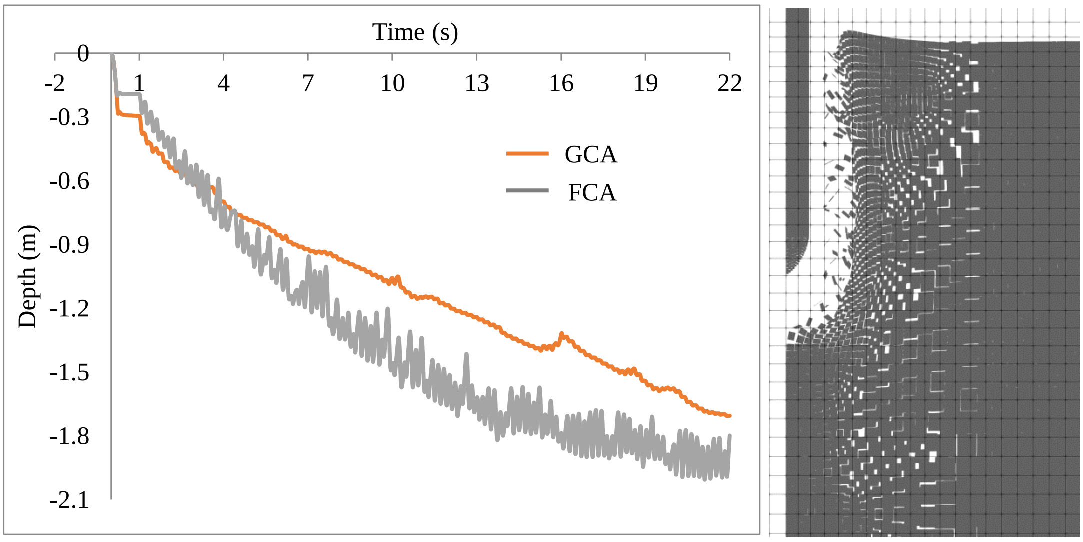

Figure 4 Penetration curve for dense sand using the GCA and FCA (left); oscillations observed near the pile in frictional contact (right)

In comparison to frictional contact, the Geo-contact approach provides a smooth interaction between the soil and pile, and has a much smaller gap. The non-physical gap is due to the difference in stiffness characteristics of each material. The soft material nicely absorbs the impact and responses accordingly during the interaction. This can be observed in Figure 3, where the radial stresses are shown during an impact on the soil during pile installation. Very high radial stresses are observed in the soil domain when using FCA, which reaches deep into the soil. With the GCA, the stresses are lower and localised due to the additional smoothing of the non-physical oscillations provided by the penalty function.

The differences in the algorithms directly influence the penetration rate; for example, FCA penetration rate is less computationally intensive thus faster than that of the Geo-contact one. FCA also causes the pile to retract more after each blow resulting in high amplitude oscillations associated with the high impact forces applied on the soil, which in turn amplifies the errors and obstructs the simulation by heavily deforming the particles. This can be observed in Figure 4, where the particles are heavily distorted in the soil domain. A huge gap between the pile and soil is also observed with FCA where the forces are applied as soon as the contact pair is detected over the nodes. For the same mesh, Geo-contact produces a smaller gap by applying the forces smoothly according to the penalty function based on the actual position of the particles not by the nodes.

When comparing the predicted penetration curves of loose sand using the GCA and PCA, we observe that the use of the PCA alone provides the smooth interaction, but the pile penetration curve is almost linear, which is different than one would expect as the resistance should increase with the depth. This is mainly due to the interaction happening between the linear elements rather directly with the actual pile and soil particles. In Figure 5, void ratio distribution can be seen in the soil region for Geo-contact case. Here the soil around the pile shaft is densified by the action of pile movement as might be expected (Mahutka et al., 2006). The densification region extends to a distance of 3D (D - diameter of pile). A small region of dilation can be seen near the pile tip upto a distance of 0.5D; see, e.g., Henke & Grabe (2006).

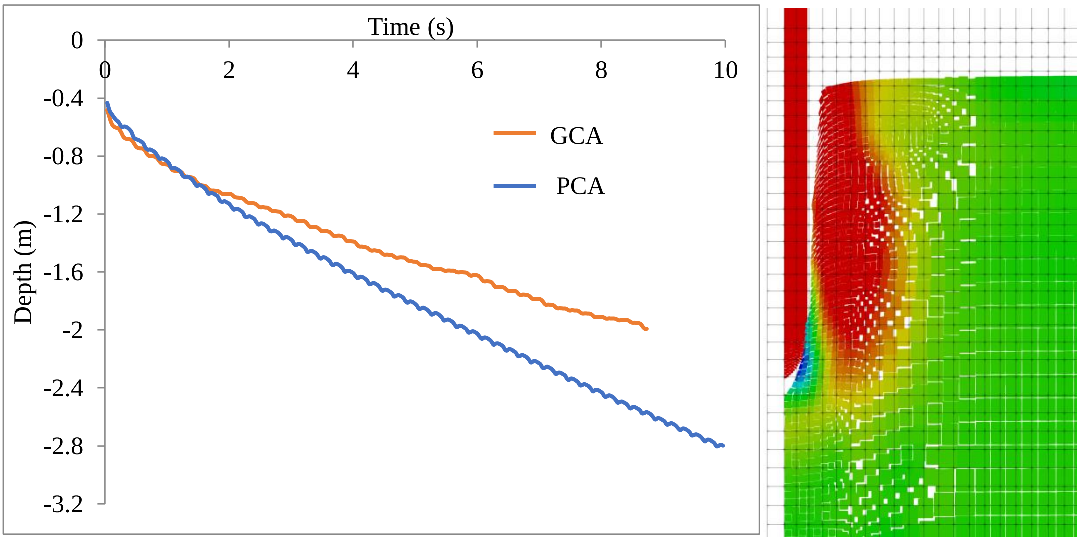

Figure5Penetration curve for loose sand using PCA and GCA (left); void ratio distribution in loose sand using GCA (right); Note: red – compaction, blue – dilation, green – initial void ratio outside zone of pile influence.

CONCLUSION

The GCA presented in this paper in combination with a CPDI scheme mitigates the non-physical interaction problems, observed in the past between bodies that differ in stiffness. This is a common scenario in case of geotechnical simulation where the soil is softer than the other interacting body. The Geo-contact approach provides a smoother and physically acceptable interaction between the soil and structure during the pile installation as shown for the two cases presented herein.

The FCA fails to simulate highly dynamic processes due to the oscillations caused by the contact forces. Although the frictional contact predictions can be improved via mesh refinement near the pile tip, it still cannot match the quality of prediction provided by the Geo-contact. Penalty contact from Hamad et al. (2017)produces similar results as that of GCA but at additional computation costs associated with a higher number of particles and with more difficulties in modeling.

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