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Parameter study for the effective pile installation in saturated sand using Material Point Method (MPM)

Etude de paramètre pour l'installation de pieux efficace dans le sable saturé à l'aide de la Material Point Method (MPM)

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ABSTRACT: Installation of pile in saturated soil is a dynamic process involving soil-water-structure interactions. During the process, large deformation in soil is also observed. Simulation of large deformation and multiphase materials require a robust and stable numerical approach. Finite Element Method (FEM) fails to model such cases by posing mesh distortion problems. For which, Material Point Method (MPM) is a robust method developed by considering features from Lagrangian and Eulerian approaches. Here, the particles move over the fixed mesh eliminating the mesh distortion and boundary conditions are provided to the fixed mesh. The numerical investigation of pile installation will reduce cost and time for on-site testing by providing basic estimation. For this, a 2D axisymmetric model is considered with two-phase formulation to model saturated soil. Pile installation is made by vibration and impact loading. Output variables such as pile displacement, soil stress states, void ratio, water pressure etc. provide the information on the installation process. Based on these, installation parameters such as frequency of loading, maximum dynamic load, skin friction are calibrated to achieve the optimal results.

RÉSUMÉ: L'installation de pieux dans un sol saturé est un processus dynamique impliquant des interactions sol-eau-structure. Au cours du processus, une déformation importante du sol est également observée. La simulation de grandes déformations et de matériaux multiphases nécessite une approche numérique robuste et stable. La méthode des éléments finis (FEM) ne permet pas de modéliser de tels cas en posant des problèmes de distorsion du maillage. Pour laquelle, la méthode des points matériels (MPM) est une méthode robuste développée en prenant en compte les caractéristiques des approches lagrangienne et eulérienne. Ici, les particules se déplacent sur le maillage fixe en éliminant la distorsion du maillage et des conditions aux limites sont fournies au maillage fixe. L'investigation numérique de l'installation de pieux réduira les coûts et la durée des tests sur site en fournissant une estimation de base. Pour cela, un modèle 2D axi-symétrique est considéré avec une formulation en deux phases pour modéliser un sol saturé. L'installation des pieux se fait par vibration et par impact. Les variables de sortie telles que le déplacement des pieux, les états de contrainte du sol, le taux de vide, la pression de l'eau, etc. fournissent des informations sur le processus d'installation. Sur cette base, des paramètres d'installation tels que la fréquence de chargement, la charge dynamique maximale, le frottement de la peau sont calibrés pour obtenir des résultats optimaux.

Keywords: MPM; CPDI; pile installation; large deformation.

1 OVERVIEW

Installation of pile by driving into soil requires a dynamic load. Based on the load application, it can be performed by various methods such as vibratory driven, impact driving (hammering), hydraulic press-in etc. These methods achieve the basic requirement for a pile installation i.e. pile embedment depth. But the installation procedure, the impact on the soil especially on the status variables like void ratio and stress status - on the effects on the pile (fatigue), on possible set-up behaviour and on environment are completely different. Thus it is a decisive task to identify an effective installation method. Based on field studies over the past decades it has been observed that the vibratory driving methods outperform the impact driving methods with regard to the installation process in most cases as there are several advantages of vibro-driving piles such as faster penetration rate, lesser ground vibrations, low impact on the adjacent structures, very low noise levels etc. This largely takes care of environmental issues involved in the projects. Further impact driving method requires more complicated and expensive equipment whereas vibratory driving requires only vibrators attached to the top of the pile (Jonker, 1987).

The vibratory driving process engages various parameters to be considered for effective pile installation but also for optimal pile behaviour due to axial or lateral loading. Therefore a major task is the identification of appropriate installation parameters.. The execution of field tests to identify optimised installation parameters would be expensive and time consuming. Even the study of influenced soil parameters due to the installation becomes demanding. This urges to consider a numerical approach which can be used for intensive study the installation process and the bearing behaviour of vibratory driven piles. As the installation process involve large deformations near the pile tip, FEM fails to simulate due to the mesh distortion. In that case, MPM – a mesh based particle approach where the particles move over a fixed computational mesh - provides a stable approach to simulate large deformation.

In the present work, an advanced variant of MPM called Convected Domain Particle Interpolation (CPDI) proposed by Sadeghirad et al. (2011) is used for the simulations. This method eliminates certain numerical oscillations observed in standard MPM (Sulsky et al., 1994). Further usage of penalty contact algorithm and hypoplastic constitutive model enhances the approach to deal with the dynamic process.

The paper is organised with three sections which provides the background of numerical approach and then a section to explore pile installation methods. Finally the assessment is made by the simulations to analyse the efficient installation procedure.

2 NUMERICAL METHOD

Material Point Method (MPM) is the numerical method used to simulate the pile installation process. This selection is based on several studies where it is justified that the method can handle large deformation problems better than lagrangian approaches like Finite Element Method (FEM) (Moormann et al., 2018). In FEM, the body is discretised into nodes and elements where the governing equation are solved on the nodes and move according to the solution. This is suitable for small deformation where the Jacobian of the element is maintained even after certain deformation. But in geotechnical problems, large deformation is commonly observed. It is difficult and inefficient to avoid mesh distortion in basic FEM procedure, even though trials like adaptive mesh technique, remeshing procedures are adopted to improve the mesh. Whereas in MPM, the body is descritised into particles which move over a fixed computational mesh. The governing equations are solved on the nodes of computational mesh and then interpolated to the particles. Finally the mesh is reset back to the original shape and the particles move; thereby avoiding the mesh distortion to capture large deformation.

The MPM suffers from grid-crossing error when the particles move from one cell to another. This is mainly due to the sudden change in the derivatives of internal forces as a consequence of using linear shape functions. In order to avoid this, higher shape functions are suggested. But the costs increase with higher shape functions. So, another procedure proposed by Bardenhagen & Kober (2004), where the interpolation is enhanced by providing spatial domain to the particles. Further Sadeghirad et al. (2011) proposed Convected Particle Domain Interpolation (CPDI) which accomodated the deformation of the particles through the deformation gradient over the entire domain.

To incorporate effects of water in the saturated sand, two-phase model is implemented into the CPDI approach. Here, multi-velocity approach is considered with a single particle to represent the saturated soil. This enables us to monitor the pore water generation and dissipation during the pile installation process. It also helps in capturing the liquefaction effects.

A hypoplastic constitutive model is used to model the soil. The non-linear model is developed by von Wolffersdorff (1996) with the addition of intergranular strain concepts by Niemunis & Herle (1997). In this model the stress state of the granular material is determined by the void ratio and intergranular strains.

Together with all necessesary tools, simulation of pile installation is performed to study the effects of installation parameter in saturated sand for an effective installation.

3 PILE INSTALLATION

Among several methods for driving a pile into saturated sand, hammering and vibration is considered in this work. Vibratory driving has usually advantages in comparison to hammering. Following are the favourable features of vibration listed by Saleem (2011) and Martinkus et al. (2015):

- Ease of vibratory system installation,
- Higher capacity of vibrators can be achieved by joining individual together,
- Faster installation rate,
- Low cost - due to the simpler system and quick installation,
- Less impact on pile (e.g. fatigue),
- Low noise and low disturbances to the adjacent structures. This is a crucial due to the environmental concerns and location of pile installation.

Further, many parameters involved in the vibration procedure can be monitored to increase the efficiency. Among them, driving frequency plays an important role in achieving best practice. Due to higher costs involved in performing in-situ analysis, use of numerical methods justifies the purpose.

The effects on the soil by vibration are notably observed. The pore water pressure generation and dissipation has a specific role due to the vibration. During impact driving, there exists often enough time for the dissipation of pore water pressure which is generated during the hammering. But in case of vibration as the frequency of loading is high, dissipation is difficult. Due to this, pore pressure gets really high, tending the effective stress in the soil to zero. The effect is referred to as liquefaction. Reduction in effective stress favours the penetration and makes the pile installation easier.

4 SIMULATION

To study these effects and to obtain an efficient installation procedure, simulation of the pile installation is performed in saturated sand using an axisymmetric formulation (Hamad, 2016).

Various simulations have been considered to obtain the data for a study on installation procedure. First, an installation is made using hammering and another with the vibration loading. A brief comparison is made to study the effects on soil by the two installation methods. Further vibratory driven installation is performed with different frequencies ranging from 15 Hz to 30 Hz. Finally, at 15 Hz, installation is performed with different values for friction coefficient. By this, the effects on the soil can be observed as basis for achieving appropriate parameters.

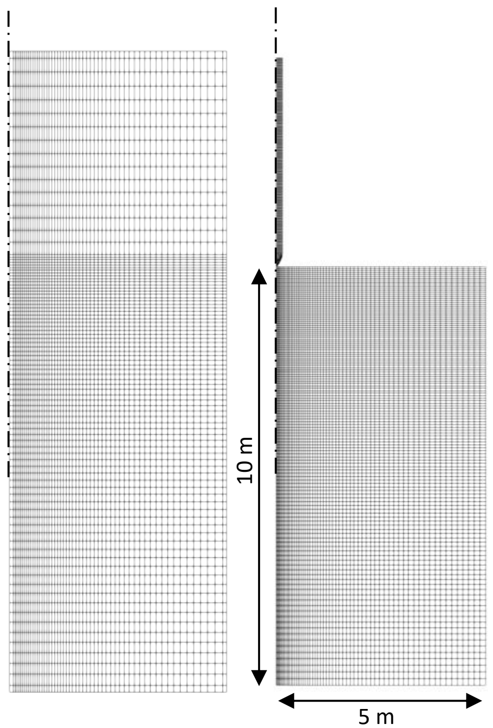

Figure 1. Initial configuration for the pile installation; left – computational mesh and right- particle mesh

A 2D axisymmetric model is considered for the installation of a 5 m long pile into Lausitz sand as shown in the Figure 1. The sand is fully saturated and the hypoplastic constitutive model is used for the properties of Lausitz sand (See Table 1). The dry density of the sand, ρ_d = 1800 kg/m^3 and the initial void ratio is taken as e_0 = 0.5, which corresponds to medium dense sand. The sand domain is 10 m in height with the width of 5m. Pile is modelled with linear elastic material model with Young's modulus (E) = 200 GPa, Poisson's ratio (ν) = 0.3, density (ρ) = 3000 kg/m^3. Roller boundaries are provided on the sides and fixed boundary at the bottom.

The numerical model and the material properties are kept same for all the simulation.

Table 1. The hypoplastic material properties for Lausitz sand (Herle & Gudehus, 1999).

$\phi(^o)$	$h_s(GPa)$	n	e_{d0}	e_{c0}	e_{i0}
33	1600	0.19	0.44	0.85	1.0

α	β	m_r	m_t	R
0.25	1.0	5	2	10^{-4}

β_r	χ	e_o
6	0.5	0.50

4.1 Loading due to impact and vibratory driving

Impact driving is simulated by applying 70 kN of force, which is applied as traction on top of the pile (i.e. 1000 kPa). The load is applied as a sinusoidal pulse at 2 seconds interval between each blow. The interval between the blows is evident due to the hammering mechanism.

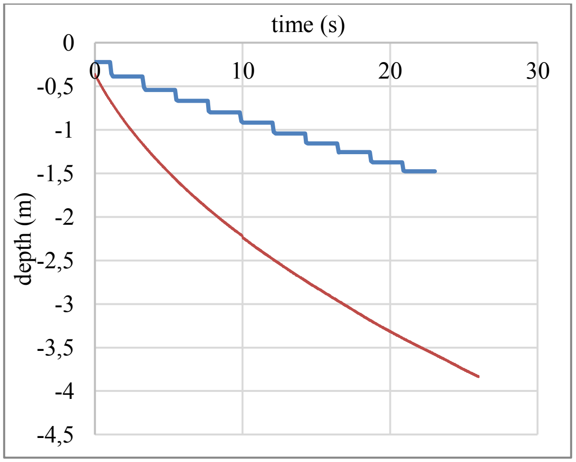

Figure 2. Penetration curve for hammering and vibration.

The simulation is performed for the first 25 seconds of installation. Figure 2 shows the penetration curve for the two methods. Here, the vibration loading clearly shows that the penetration process is significantly faster due to vibration than the hammering process. Even if the interval of hammering is reduced to 1 s, the rate of penetration cannot match the vibration driven pile. As mentioned by Saleem (2011), the vibration loading can be faster up tp 3 times of hammering.

4.2 Frequency

As the vibration loading has flexibility in varying the frequency, it leaves to decide upon the optimal value. The penetration rate, effect on the soil, bearing behaviour of the pile etc. are to be studied in order to select an appropriate frequency. For this, a simulation is performed using vibration loading by varying the frequency from 15 Hz to 30 Hz in the intervals of 5 Hz. The maximum dynamic force from the vibrator is kept constant to 70 kN during these tests. The pile penetration curve for the different frequencies is shown in Figure 3. It can be observed that the increase in frequency will decrease the rate of penetration.

The effect on the soil can be observed through the change in void ratio. In Figure 4, comparison of void ratio distribution after the penetration of 2.5 m by 15 Hz and 30 Hz vibration is shown. Here, the soil densification can be seen around the pile shaft in both the cases but the extent of it is different. Densification region extends up to 4D (D – diameter) in case of 15 Hz loading and around 2D for 30 Hz loading.

The excess pore pressure shown in Figure 5 is measured for the 15 Hz loading at a depth of 1 m and 10 cm away from the pile surface. Here, the excess pore pressure is observed to reach a higher value (-33 kPa) as the pile tip approaches the monitoring point and later maintains a value of -15 kPa which is higher than the initial value at this location.

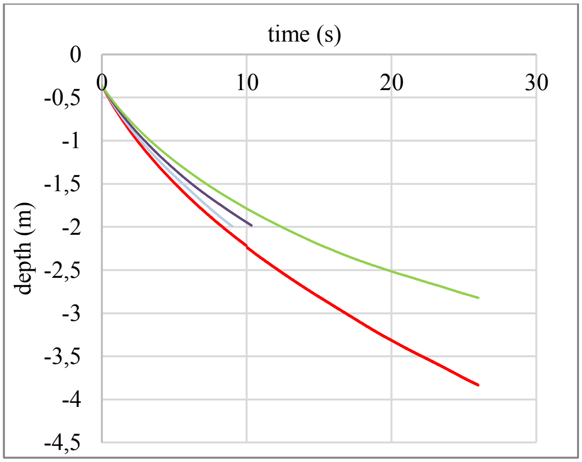

Figure 3. Penetration curve for different frequencies in vibration loading; 15, 20, 25 and 30 Hz from the bottom respectively.

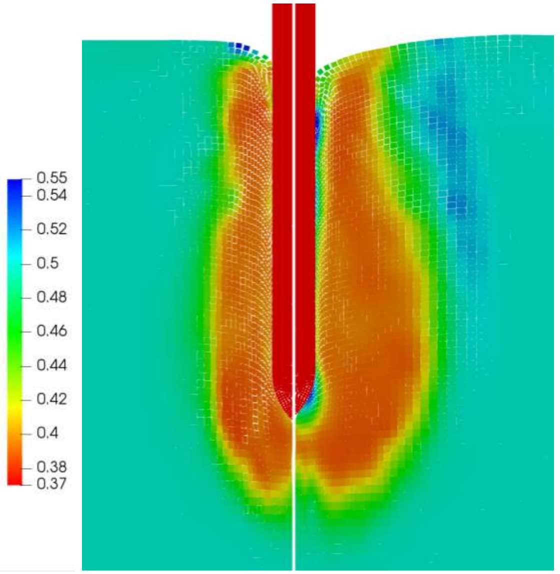

Figure 4. Void ratio distribution during the installation with vibration at 30 Hz (left) and 15 Hz (right). Initial void ratio = 0.5.

This suggests the increase in pore pressure around the pile surface for the entire duration of pile installation. As the pore pressure increases, effective stress of soil decreases which allows the pile to penetrate faster (Rodger & Littlejohn, 1980).

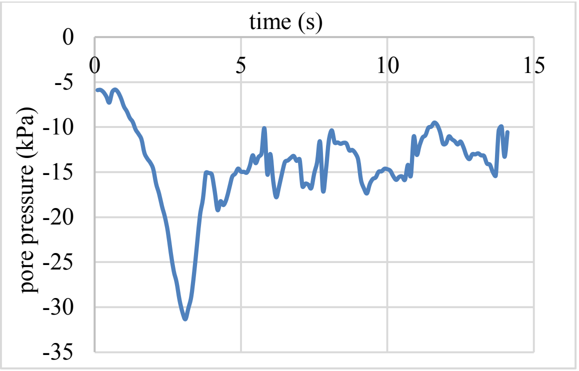

Figure 5. Excess pore pressure development at a location 10 cm away from the pile and 1 m deep from the surface.

4.3 Friction coefficient

The interaction between the soil and pile is modelled with Penalty contact method where the friction is incorporated using Mohr-Coulomb friction law. This helps to predict the effect of pile surface smoothness in the installation process. The penetration curve is shown in the Figure 6, where the three different values for coefficient of friciton (μ=0.15, 0.3 and 0.4) are used. The installation is performed by vibration with frequency of 23Hz. Here, it is clear that the smoothness of pile surface affects the penetration slightly. More the pile surfaces comes in contact with soil, resistance increases and becomes slower. Whereas at initial depths, we can see little to no effect by different roughness.

5 CONCLUSION

The installation of a full diplacement precast pile is performed using advanced MPM i.e. CPDI, together with non-linear hypoplastic model and two-phase formulation. This provides a good platform to study the complex dynamic processes enabling us to investigate more with the installation parameters in order to obtain greater efficiency.

The simulations of pile installation by hammering and vibration give insight to the benefit for vibratory driven installation of piles. Faster penetration, easy set-up and machinery, low noise etc. are the best features of vibratory driven piles. Further enables us to explore various loading frequency to observe the behaviour of soil and on the installation. Also, the effect of roughness of pile shaftis demonstrated with the simulation of various friction co-efficients.

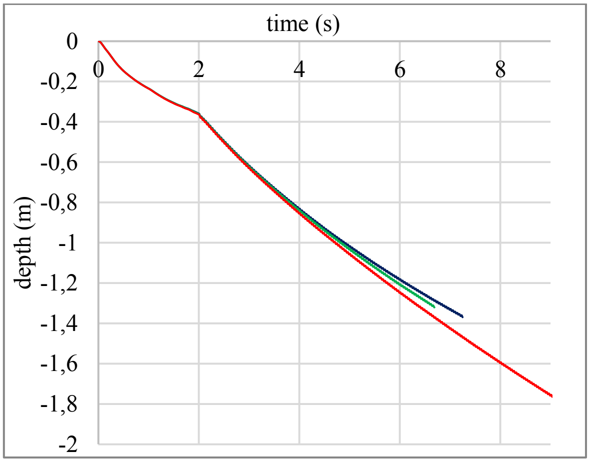

Figure 6. Penetration curve for different friction coefficient; μ= 0.15, 0.3, 0.4 from the bottom respectively.

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