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Numerical simulation of vibrocompaction based on CEL approach

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ABSTRACT: A numerical model is set up to simulate the densification of dry sand using the vibrocompaction method. This compaction method includes densification of loose sands by means of shear deformation processes imparted by horizontal vibrations of vibrator probe at the required soil depth. A cylindrical stay-tube and vibrator probe assembly are numerically modelled in the centre of cylindrical sand domain of 40 m depth based on the CEL approach. At the beginning of the deep vibration compaction simulation process the vibrator is simulated wished in place at a penetration depth of 20 m. The compaction process between 20 to 10 m depth, is modelled based on the pilgrim step method similar to the compaction procedure followed on field. A hypoplastic constitutive model is used to characterize the stress-strain behaviour of the sand. The effect of saturation of sand layer, shape of the vibrator and spacing of the compaction points on extent and degree of compaction is studied.

Keywords: CEL; vibrocompaction; hypoplastic; compaction; sand

1 INTRODUCTION

Ground improvement methods are a good technique to reduce the risk of soil failure. The vibrocompaction method is an established ground improvement technique. It is used to improve the properties of loose to medium dense granular soils by compacting deep layers of the soil and therefore reducing settlements and aids in liquefaction mitigation (Massarsch and Fellenius, 2001). This compaction method includes densification of loose sands by means of shear deformation processes imparted by horizontal vibrations of vibrator probe at the required soil depth.

Numerical simulations of the method would help develop an insight and also optimize the technique (Arnold and Herle, 2009). Numerical simulations of the vibrocompaction compaction technique using the Coupled Eulerian Lagrangian CEL approach has been carried out.

2 VIBROCOMPACTION

The vibro compactor consists of an unbalanced mass inside a steel tube. The mass located inside the tube is rotating around the vertical axis of the compactor such that the compactor is oscillating during the compaction process. Therefore, the vibration energy is directly transferred from the tube to the surrounding soil.

The main body of the vibrator is of 5.0 m length and a diameter of 0.47 m. The tube is pin jointed to a stay tube, which has the same diameter as the steel tube and is carried by a crane (Witt, 2009).

The modelled vibrator has a vibration frequency range from 15 to 30 Hz and equivalent horizontal force of 520 kN at 30 Hz.

The pilgrim step method of compaction is observed on field. During this method the vibrator is pushed down and pulled up stepwise with a compaction time of 30 to 60 s for each step. Step heights in the range of 0.3 to 1.0 m are generally used in practice.

The mass located inside the tube rotates around the vertical axis of the compactor. This results in an centrifugal force that is imparted to the soil while the vibrator undergoes oscillating movement, during the compaction process. Shear waves in the soil resulting from the energy of the vibrator lead to the compaction of the soil. The soil from adjacent regions will move into the resulting void spaces. This movement can be noticed as a settlement of the ground surface.

3 NUMERICAL MODELLING

3.1 Coupled Eulerian Lagrangian (CEL)

The numerical simulation of vibrocompaction method is a problem involving large deformations, hence coupled Eulerian-Lagrangian (CEL) can be used for this type of problem. This method combines the advantages of the Lagrangian analysis with those of an Eulerian formulation. A characteristic of the Lagrangian formulation is the deformable mesh which moves with the material meaning that the movement of a continuum is described as a function of time and material coordinates. In an Eulerian analysis on the other hand the movement of a continuum is formulated by a function of time and spatial coordinates. The mesh of an Eulerian formulation remains undeformed and the material can move freely through the mesh.

3.2 CEL Model

A three-dimensional model based on the CEL method (Qui et al., 2012; Nagula et al., 2017) as depicted in Figure 1 is created. The soil body is modelled as an Eulerian domain and has a diameter of 40 m and a height of 50 m. A void area of height 1 m is located above the soil to allow the material to move into this space during the simulation. The vibrator is modelled as a Lagrangian body of 5 m length and 0.47 m diameter wished in place at a preinstalled depth of 20 m. The vibrator is vertically hinged to the stay tube which has the same diameter as the vibrator. The stay tube is fixed in horizontal and vertical direction at its upper end. Both tools are modeled as a linear elastic material behavior with material properties of steel. The contact between the compactor and the soil is frictionless.

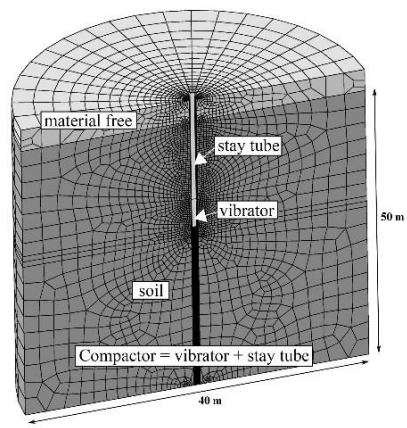

Figure 1. Vertical cut through the CEL model

3.3 Hypoplastic Constitutive Model

The material behavior of sand was modeled by the Hypoplastic model developed by von Wolffersdorff (1996) and further extended for intergranular strain by Niemuns and Herle (1997). The model is suitable for modeling the behavior of granular materials as it can capture phenomenon such as dilatancy, contractancy, the dependency of stiffness and strength on the pressure and the void ratio, as well as a different stiffness for loading, unloading and reloading.

The material properties of ‚Kippen Sand‘are as tabulated in Table 1.

Table 1. Hypoplastic Model parameters for Kippen Sand

Material Parameter	Value	Description
φ_c	32.97 °	Critical state friction angle [°]
h_s	195	Granular hardness [MPa]
n	0.168	Exponent
e_{d0}	0.672	Minimum void ratio
e_{c0}	1.116	Critical void ratio
e_{i0}	1.283	Maximum void ratio
α	0.248	Exponent
β	1.03	Exponent
m_T	2.78	Stiffness ratio at 90˚ change of direction
m_R	3.69	Stiffness ratio at 180˚ change of direction
R	0.0000 12	Maximum value of intergranular strain
β_R	0.3	Exponent
X	6	Exponent
e	0.96	Initial void ratio

3.4 Simulation Steps

The deep vibration compaction process is simulated based on the following simualtion steps:

1. Initial Phase: The initial state parameters are calculated based on the K_0-stress state.
2. Compaction Phase: The vibrator is wished in place at a depth of 20 m. In order to replicate the force applied by vibrator, nodal forces both in x and y directions (horizontal plane) calculated according to the frequency of vibration, were applied at the tip of the vibrator. Sinusoidal amplitude at corresponding frequency was applied to the nodal forces in order to simulate the horizontal vibration of the vibrator which leads to the compaction of the surrounding sand layers. A compaction time of 5 s at each compaction depth was considered (Note: It was found that by comparing real field measurements and simulation results that compaction in real time of around 30 s is comparable to 5 s simulation time.)
3. Push Down Phase: After 5 s of compaction the vibrator (while vibrating) is pushed down by 0.5 m in 1 s.
4. Pull Up Phase: The vibrator is then followed by pulling up by 1 m in 1 s

Step 2 to 3 are then repeated in sequence till compaction is achieved between depths of 20 m to 10 m in step heights of 0.5 m.

3.5 Series of Analysis

The vibrocompaction method of compaction is simulated for a depth between 20 to 10 m. This was followed by series of parametric studies which analysed the effect of frequency of compaction, shape of vibrator and spacing of compaction points on the degree and extent of compaction.

4 NUMERICAL SIMULATION RESULTS

The following section firstly discusses the feasibility of the CEL method to model such a complex process in terms of the results of the numerical simulation of the deep vibration compaction process. Secondly it analyses the effect of the various influencing factors as discussed in the previous section on the extent and degree of compaction.

4.1 Compaction by Vibrocompaction

Figure 2 depicts the evolution of void ratio around the vibrator after the compaction between 20 to 10 m depth. It can be observed that the void ratio around the path followed by the vibrator, has reduced substantially indicating compaction of the loose Kippen sand layer.

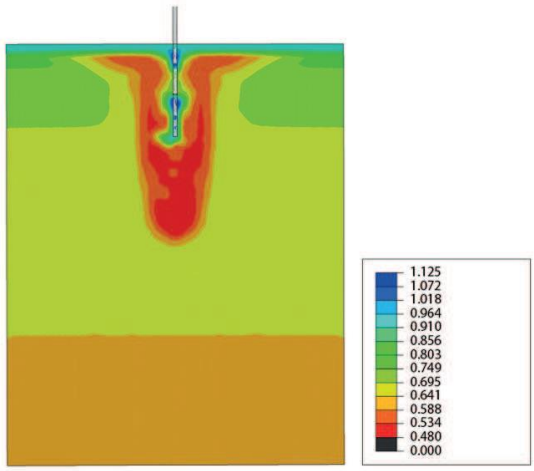

Figure 2. Evolution of void ratio between 20 to 10 m depth after compaction

4.2 Influence of Frequency

Compaction was carried out at different frequencies namely 15, 20, 25 and 30 Hz. The corresponding centrifugal forces were also varied accordingly. The effect of frequency on the extent and degree of compaction was studied. It is to be noted that the simulation were carried out only for one compaction step at a depth of 20 m and not for entire depth. Figure 3 describes the evolution of void ratio around the vibrator at 20 m depth for the various frequency cases. It can be observed that at 15 Hz both the extend and degree of compaction is reduced compared to the other other frequencies. It is also interesting to observe that compaction at 20 Hz leads to nearly the same values as at 30 Hz. Compaction executing at lower frequency can lead to substantial reduction of wear of the motor eventually leading to cost reduction (Massarsch and Fellenius, 2001).

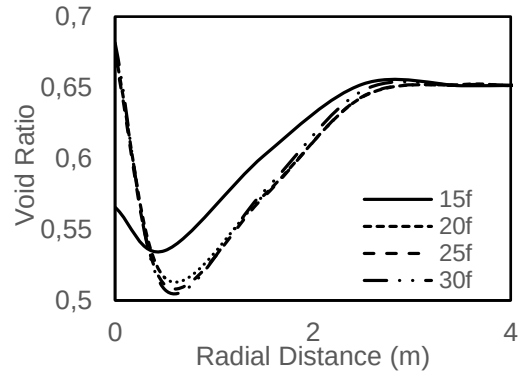

Figure 3. Evolution of void ratio around vibrator at 20 m depth at different frequencies

4.3 Effect of Shape of Vibrator

Vibrators in real life generally consist of wings (shafts) on the side and are believed to improvise compaction. Simulation were carried out with two different forms of vibrators, one consisting a simple cylindrical solid tube and the other replicating the exact shape of the vibrator with wings (Figure 4). Simulations for the case were carried out with friction . Coulomb's friction law with wall friction co-efficient $\mu = \tan(\varphi_c)$ was chosen.

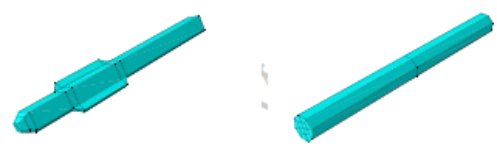

Figure 4. Vibrator model with (left) and without wings (right)

Figure 5 describes that a vibrator with wings leads to more uniform compaction even if the magnitudes of void ratio achieved is nearly similar. This observation can be attributed to the fact that wings provide extra surface area for soil and vibrator interaction. This factor needs further simulations and analysis in order to fortify the concept.

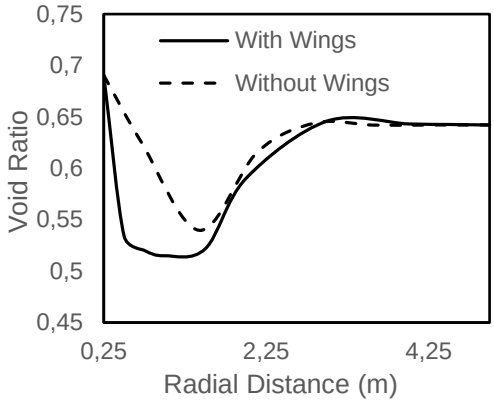

Figure 5. Void ratio development around vibrator with and withour wings

4.4 Spacing of Compaction Points

The spacing of adjacent compaction points on the grid plays an important role in terms of the efficieny of compaction of the whole test grid area. The spacing usually is decided based on trial tests on field. Intutively it is felt that closer spacing would lead to better compaction. In order to comprehend the effect of spacing on the efficiency of compaction, simulations were run at different spacings. After the execution of one compaction point between depth 20 to 10 m, the results were imported to a new model and another set of simulations were run for an adjacent compaction point at varying spacing distances. In Figure 6 it can be observed that very close spacing less than 3 m can lead to a smaller compaction zone. Spacing of 4 and 4.5 m leads to a uniform and larger zone of compaction with no tapering towards deeper depth like in other cases, see Figure 6.

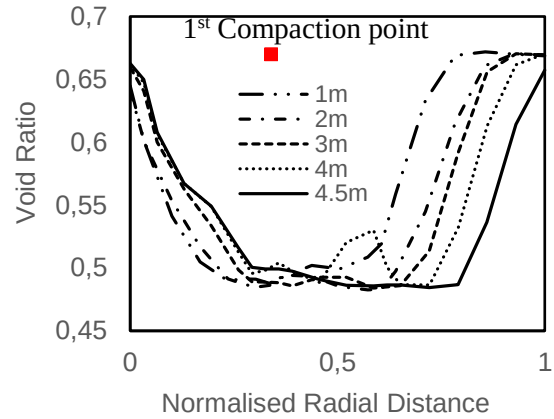

Figure 6. Variation of void ratio developemnt around compaction points with spacing at 16.5 m depth

5 CONCLUSIONS

The primary simulation analysis of vibrocompaction of ‚Kippen Sand‘ establishes the effectiveness of CEL to model such complicated process. The degree and extent of compaction is affected by frequency. An optimised frequency can be chosen balancing the effectiveness of compaction and cost of operation. Simulations can help acertain optmised spacing between compaction points. The next leg of analysis would include designing an optimised deep vibration compaction process where the nature of process, frequency, rate of movement of vibrator and spacing are optimised in order to yield best compaction in least possible consumption of resources.

6 REFERENCES

Arnold, M. Herle, I. 2009. Comparison of vibrocompaction methods by numerical simulations. *International Journal of Numerical and analytical methods in Geomechanics* **33**, 1823 - 1838.

Massarsch, K.R. Fellenius, B.H. 2001. Vibratory Compaction of Coarse-Grained Soils, *Canadian Geotechnical Journal* **39**(3), 25.

Nagula, S., Grabe, J., 2017. 2-Phase dynamic simulation of deep sand compaction to reduce

liquefaction. In: *10th International conference on structural dynamics Eurodyn-2017* (Vestroni, F., Romeo, F. and Gatutulli, V. (eds)), Procedia Engineering **199**, 2396-2401.

Niemunis, A. Herle, I. 1997. Hypoplastic model for cohesionless soils with elastic strain range. Mechanics of Cohesive-Frictional Materials 2, 279-299.

Qiu, G. Henke, S. Grabe, J. 2009. Application of coupled eulerian lagrangian method to geomechanical problems involving large deformation. Proceedings of SIMULIA Customer Conference 2009, London.

Witt, K.J. 2009. Grundbau-Taschenbuch, Teil 2: Geotechnische Verfahren, Ernst&Sohn, Berlin.