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2-Phase dynamic simulation of deep sand compaction to reduce liquefaction

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Abstract

A numerical model of a shallow foundation resting on sand is set up to simulate the liquefaction of partially saturated sand subjected to a confined transient loading. The foundation is observed to undergo large settlements due to liquefaction of sand. In order to analyze the feasibility of deep vibration compaction in liquefaction mitigation, saturated sand was subjected to compaction and later the same compacted sand with foundation was subjected to a confined transient loading. It was observed that the compaction technique reduced liquefaction drastically, suggesting that deep vibration compaction can be effectively used as a liquefaction mitigation measure.The 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 coupled hypoplastic constitutive model is used to characterize the stress-strain behavior of the saturated sand.

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Keywords: Liquefaction;2-phase;Hypoplastic;Saturated sand

1. Introduction

The deep vibration compaction 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. Numerical simulations of the method would help develop an insight

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on the feasibility of the method for liquefaction mitigation [1]. Numerical simulations of liquefaction of saturated sand and that of the deep vibration compaction technique was modeled using the Coupled Eulerian Lagrangian CEL approach. Coupled 2-phase Hypoplastic model was used to model the saturated sand behavior.

A cylindrical sand domain of 30m height and 30m radius was considered so as to minimize the effect of reflected stress-waves at boundaries. Acceleration time history for the El Centro Earthquake 1940 in California, USA as confined transient loading was considered. In the first phase of the simulations the saturated loose sand domain with foundation resting on the ground surface was subjected to transient loading for a period of 2 seconds and the associated liquefaction phenomenon in the loose saturated sand was observed. In the second phase of simulations the loose saturated sand was subjected to deep vibration compaction. This technique leads to a dense packing of the soil in an area with a radius of 0.6 until 1.75 m around the compactor [1, 2]. The obtained stress state changes in the saturated sand due to the compaction were exported to a new numerical model and the same model was again subjected to confined transient loading in order to study the feasibility of deep vibration compaction in order to reduce liquefaction.

2. Numerical Modeling

2.1 Coupled Eulerian Lagrangian (CEL)

The numerical simulation of liquefaction and deep vibration compaction 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. Both techniques are depicted in Fig. 1.

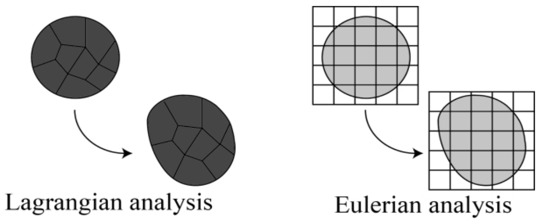

Fig. 1.Deformation of a continuum in a Lagrangian (left) and an Eulerian analysis (right) [3].

During a coupled Eulerian-Lagrangian analysis a Lagrangian object can move into and inside an Eulerian region. The Lagrangian object can move though the region without resistance until it touches Eulerian material. Then the contact algorithm starts to act. The algorithm is implemented as a general contact formulation based on the penalty method and therefore, assumes a hard pressure-overclosure behavior, is less strict than a kinematic method and allows small penetrations of the Eulerian material into the Lagrangian object

2.2 CEL model

A three-dimensional cylindrical model of 30m height and 30m radius based on the CEL method with 57540 hexahedral elements was created. The foundation (2x2x0.5m) was modelled as a rigid body resting on the ground surface. It is modelled as a linear elastic material with the properties of concrete. The top 1m of the domain was modelled as void area in order to allow for the movement of material into the area during the simulations. The external boundaries were restrained for horizontal movement. The acceleration time history was applied as locally confined transient loading to the base of the model to a 1 m radius area as depicted in Fig. 2. It was applied to a specific zone so as to reduce the effect of reflection of waves from the boundaries. The vibrator was modelled as wished in place at a depth of 10m in the sand domain as depicted in Fig. 3. The vibrator was modelled as a rigid body of 4m of length and 0.5m in diameter connected to a stay tube of similar diameter. The stay tube is fixed and horizontal and vertical direction on the upper end. The vibrator and stay tube are modelled as linear elastic material with the properties of steel. The contact between the vibrator and soil is assumed to be frictionless and of foundation and soil is according to Coulomb's friction law.

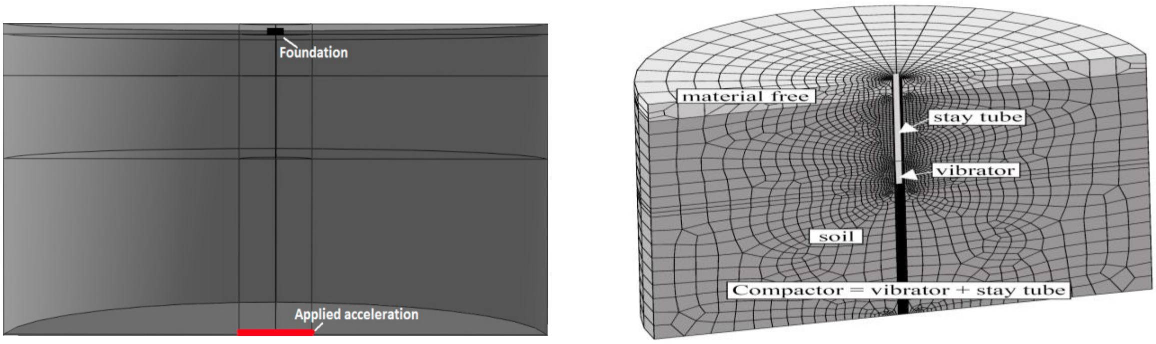

Fig. 2. Vertical cut through the Finite Element model with (a) foundation (b) compactor

2.3 Hypoplastic Constitutive Model

The material behavior of sand was modeled by the Hypoplastic model developed by Von Wolffersdorff [4] and further extended for intergranular strain by Niemuns and Herle [5]. 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. Coupled 2-phase hypoplastic model based on the u-p formulation was used in order to simulate the behavior of saturated sand. The material properties of Mai-Liao-Sand with relative density of 0.2 are as tabulated in Table 1.

Table 1: Hypoplastic Model parameters for Mai-Liao sand

Material Parameter	Value	Description
φ_c	31.5	Critical state friction angle [°]
h_s	32	Granular hardness [MPa]
n	0.324	Exponent
e_{d0}	0.57	Minimum void ratio
e_{c0}	1.04	Critical void ratio
e_{i0}	1.20	Maximum void ratio
α	0.4	Exponent
β	1.0	Exponent
m_T	2.0	Stiffness ratio at 90˚ change of direction
m_R	5.0	Stiffness ratio at 180˚ change of direction
R	0.0001	Maximum value of intergranular strain
β_R	0.5	Exponent
X	6.0	Exponent

2.4 Acceleration time history

Acceleration time history in terms of the El Centro Earthquake 1940 (California, USA) was obtained from the United States Geological Survey (USGS) database. The time history was applied as a confined transient loading to the bottom of the model for a period of 2 seconds. The acceleration versus time history as used in the simulations is depicted in Fig. 4

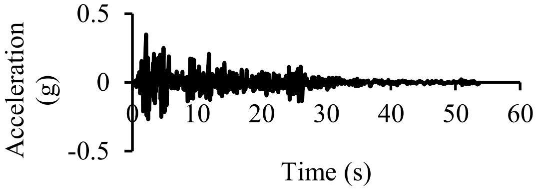

Fig. 4. Acceleration time history

2.5 Simulations

The sequence of numerical simulations was as follows:

1) Loose saturated sand domain subjected to confined transient loading for a period of 2s in order to observe the liquefaction phenomenon in loose saturated sands.
2) The second phase of simulation involved the ground improvement phase where the saturated sand domain was subjected to deep vibration compaction for a period of 5s which was followed by a drainage phase of 20s.
3) The developed corresponding stress state in the sand due to the deep vibration compaction was then exported to a new model of saturated sand domain, where the sand was again subjected to confined transient loading of 2s. The difference in liquefying behavior of loose and compacted sand was then commented upon. It is to be noted that the stress state changes caused by a single compaction point was applied to the whole of the sand domain in the last phase of simulations, assuming that in real life situations there are multiple compaction points which ensure complete compaction of the required area to be densified.

3. Numerical Results

3.1. Liquefaction

The first phase of simulations includes saturated sand being subjected to transient loading for 2s. Saturated sand undergoes liquefaction under transient loads [6] and this can be seen as decrease in effective stresses in vertical direction. It can be observed in Fig. 5 (all figures are in scale of 1:1 with respect to the model) that the effective stresses near the ground surface become zero and also the effective stress decreases with depth compared to the higher effective stress values before applying the loading.

3.2. Deep vibration compaction

The second phase of simulations involved the subjection of deep vibration compaction to saturated sand domain. Deep vibration compaction results in increase of horizontal stress in the vicinity of compaction point as can be observed in Fig. 6. It was observed that there was an increase in the horizontal stress compared to sand without compaction to the order of 1.5. The densification of the loose sand can be visualized in terms of the decrease in the void ratio around the vibrator as depicted in Fig. 7.

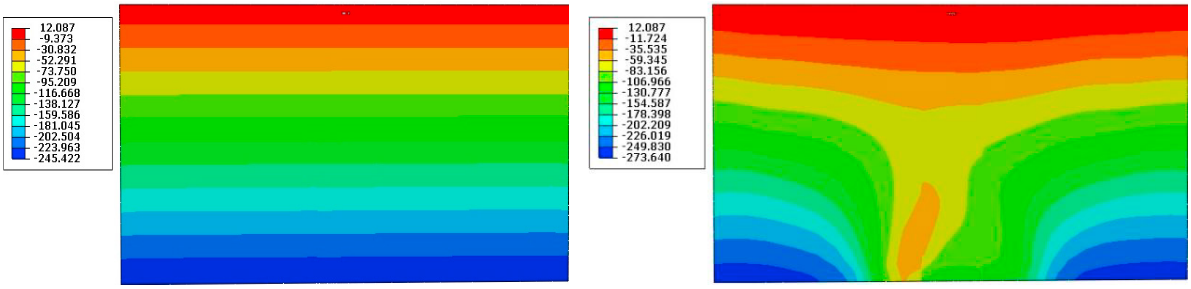

Fig. 5. Effective stress in vertical direction (a) before excitation (b) after excitation

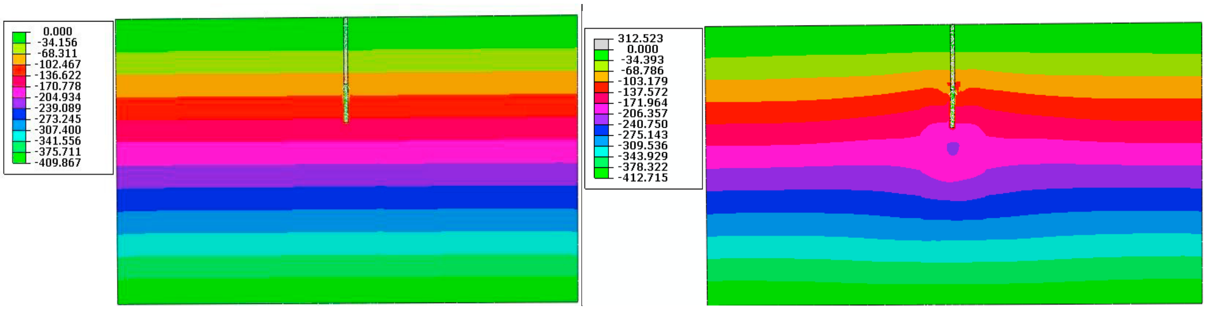

Fig. 6. Horizontal stress (a) before (b) after compaction

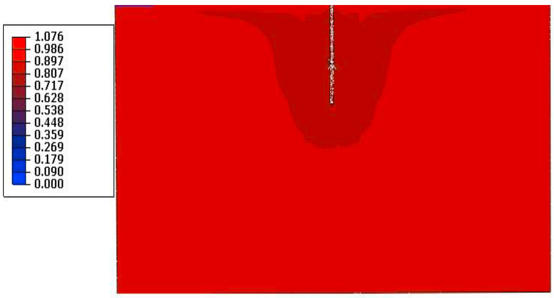

Fig. 7. Decrease in void ratio after compaction

3.3. Liquefaction Mitigation

The corresponding stress states in the saturated sand after the compaction was exported to a new model, where the sand domain with foundation was subjected to confined transient loading. There was a considerable decrease in the magnitude of excessive pore pressure generated in the saturated sand after the earthquake loading compared to the pore pressures generated in the sand without compaction (Fig. 8)

The implication of the compaction can be observed in Fig. 9 which depicts the reduction in settlement of the foundation subjected to transient load after being administered deep vibration compaction.

4. Conclusion

Saturated sands undergo liquefaction under transient loads which in turn leads to large settlements. Deep saturated sands undergo liquefaction under transient loads which in turn leads to large settlements. Deep vibration compaction leads to the compaction of sands by means of shear deformation processes. The compaction leads to an increase in horizontal stresses in the sand and reduction in void ratio. This resulting compaction ensures improved resistance against liquefaction. The reduction in generated excessive pore pressures and in settlement of the foundation re-confirms the effectiveness of deep vibration compaction methods as a liquefaction mitigation pressure.

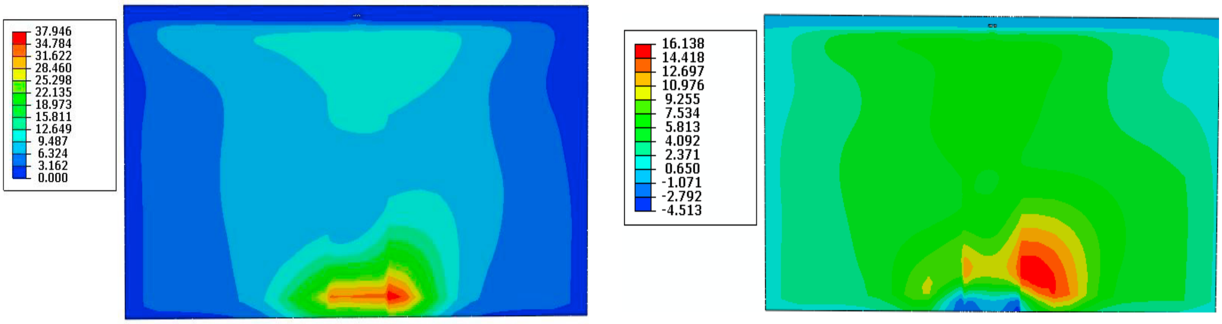

Fig. 8. Excessive pore pressure after excitation (a) without compaction (b) with compaction

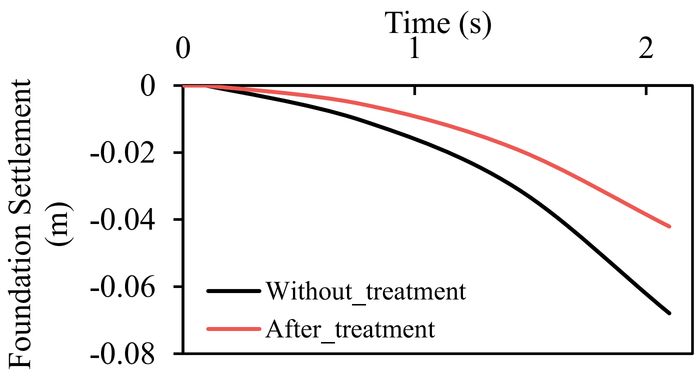

Fig. 9. Settlement reduction of foundation under excitation

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