Evaluation of soil liquefaction and its mitigation using a coupled SPH-DEM scheme

Évaluation de la liquéfaction du sol et de son atténuation à l'aide d'un schéma SPH-DEM couplé

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ABSTRACT: In this paper, a coupled fluid-particle scheme is utilized to evaluate liquefaction of saturated granular soils subjected to dynamic base excitations. The discrete element method (DEM) is employed to model the solid particles and the fluid motion is simulated using the smoothed particle hydrodynamics (SPH). A coupled SPH-DEM scheme is achieved through local averaging techniques and well-established semi-empirical formulas for fluid-particle interaction. The response of a saturated loose deposit to seismic excitation is first analyzed. As expected, the deposit exhibited significant pore pressure development and liquefaction. A liquefaction mitigation technique through the installation of gravel drains was then introduced to the deposit. Results of conducted simulations show that the gravel drains effectively reduced pore-pressure buildup, and the soil maintained its strength.

RÉSUMÉ : Dans cet article, un schéma couplé fluide-particule est utilisé pour évaluer la liquéfaction de sols granulaires saturés soumis à des excitations de base dynamiques. La méthode des éléments discrets (DEM) est utilisée pour modéliser les particules solides et le mouvement du fluide est simulé à l'aide de l'hydrodynamique des particules lissées (SPH). Un schéma SPH-DEM couplé est obtenu grâce à des techniques de moyenne locale et à des formules semi-empiriques bien établies pour l'interaction fluide-particule. La réponse d'un dépôt meuble saturé à une excitation sismique est d'abord analysée. Comme prévu, le gisement a présenté un développement de pression interstitielle et une liquéfaction significatifs. Une technique d'atténuation de la liquéfaction par l'installation de drains de gravier a ensuite été introduite dans le gisement. Les résultats des simulations réalisées montrent que les drains de gravier réduisaient efficacement l'accumulation de pression interstitielle et que le sol conservait sa résistance.

KEYWORDS: Smoothed Particle Hydrodynamics, discrete element method, liquefaction, gravel drains, liquefaction mitigation

1 INTRODUCTION

Liquefaction resistance can be improved by: increasing the soil density through compaction, stabilizing the soil skeleton, reducing the degree of saturation possibly by introducing air bubbles into the void space, dissipation of the generated excess pore pressure, and intercepting the propagation of excess pore pressures buildup, among other techniques. Herein, the focus is on gravel drains as one of the widely used liquefaction hazards mitigation method. Sadrekarimi and Ghalandarzadeh (2005) argue that the potential benefits of gravel drains include densification of the surrounding granular soil, dissipation of excess pore water pressure, and redistribution of earthquake-induced or pre-existing stress. They also note that the relatively high internal friction resistance of the gravel imparts a significant frictional component to the treated composite, improving both its strength and its deformational behavior.

The discrete element method (DEM) provides an effective tool to model granular soils and other geomaterials based on micromechanical idealizations. Numerous attempts have been made at incorporating fluid-particle interaction equations into the discrete element method formulation, including continuum-discrete methods (e.g., El Shamy and Zeghal 2005) and pore-scale techniques (e.g., Zhu et al. 1999; El Shamy and Abdelhamid 2014).

As an alternative to modeling the fluid at the pore scale, SPH could be used to approximate the set of partial differential equations represented by the averaged form of Navier-Stokes equations that accounts for the presence of the solid phase and the momentum transfer between the phases. Coupling SPH for the fluid and DEM for the solid phase offers the benefits of overcoming the need for a constitutive model for the solid phase while maintaining the robustness of DEM for large deformation problems and SPH for tracking the fluid motion. The presented model is computationally far less demanding compared to the pore-scale level models and its meshless nature makes it a powerful tool for analyzing moving boundary, irregularly shaped domains, and free surface problems. Many examples of coupled DEM-SPH application to various science and engineering problems can be found in the recent literature (e.g., Sun et al. 2013; Robinson et al. 2014).

In this paper, the results of the application of SPH-DEM to model soil liquefaction is presented. A key feature of the employed technique is that it does not presume undrained conditions for the granular deposit and allows for spatial fluid movements within the deposit. A liquefaction mitigation technique through the installation of gravel drains was then introduced to the deposit and its effect on mitigating pore pressure buildup was examined.

2 COUPLED SPH-DEM SCHEME

In SPH scheme, the fluid domain is discretized into a set of individual particles carrying local properties of the fluid such as density and pressure. The fluid pressure is obtained from the weakly compressible equation of state. The phase coupling is achieved through semi-empirical relationships between the fluid-particle interaction forces and parameters such as the local porosity and relative velocity between the two phases. An explicit time integration scheme is used to solve the equation of motion for both solid and fluid particles. Details of the model could be found in El Shamy and Sizkow (2021).

3 MODEL DESCRIPTION

The simulations were conducted on a 5.4 m high (in prototype units) saturated deposit. The lateral dimensions of the periodic deposits were chosen to be 2.5×2.5 m. The particle size range of 1.5 mm to 2.5 mm, was used in the creation of the deposits. High gravitational field of 30g was employed to decrease the dimensions of the domain. The saturated unit weight and porosity of the deposit was determined to be around 19.2 kg/m^3 and 0.44, respectively. To saturate the deposits, a fluid column with a height of 6 m and lateral dimensions of 2.5×2.5 m was built within the periodic domain using SPH particles. The high fluid viscosity of 0.02 Pa.s was used here to account for the relatively large particle sizes and to achieve a permeability close to that of coarse sand. The average shear wave velocity and low strain shear modulus of the final deposit were determined to be approximately 116 m/s and 25.8 MPa. A 3D view of the saturated deposit is shown in Figure. 1.

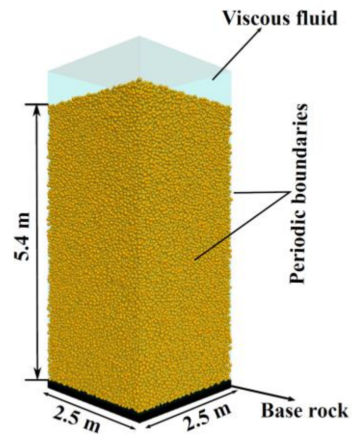

Figure 1. 3D view of the saturated deposit in conducted simulations.

In order to model the gravel drains, the arrangement shown in Figure 2a was considered as a liquefaction mitigation plan. Due to the symmetrical configuration of the drains, a small periodic domain enclosing one of the gravel drains was modeled in this study (Figure 2b). The gravel particles had a size range of 4.75 mm to 6.25 mm. To further increase the permeability of the drain, the interphase momentum exchange coefficient is reduced inside the drain to artificially increase the permeability.

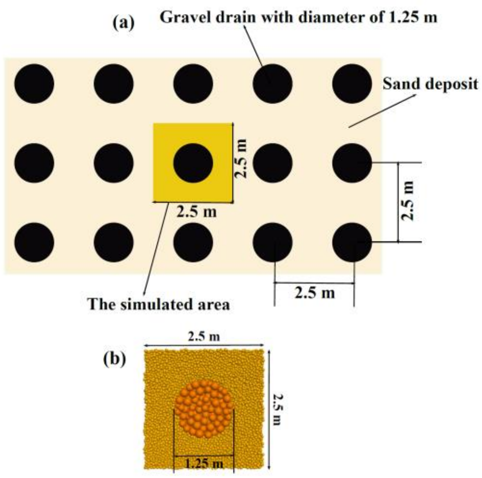

Figure 2. (a) Schematic plan view of the liquefiable zone and the drains, and (b) Top view of the deposit and the drain in performed simulation.

3 SIMULATION RESULTS

A seismic base excitation with maximum amplitude of 0.25g, frequency of 3 Hz and total duration of 13 s was applied to the models and different quantities were recorded. A pore-pressure ratio approaching a value of one indicates the excess pressure is counterbalancing the effective stress, leading to complete loss of shear strength. In case of the loose sand deposit, the top half of the deposit approached a pore pressure ratio of about 1 and slightly less than 1 for the bottom half, indicating that the entire deposit practically liquified (Figure 3). Time histories of excess pore-pressure ratio for the deposit with the drain are also shown in Figure 3. Compared to the untreated deposit, there has been considerable reduction in developed pore pressure but it was not completely eliminated by the presence of the drain. The pressure outside the drain was relatively higher than inside, indicating the fluid is migrating into the drain.

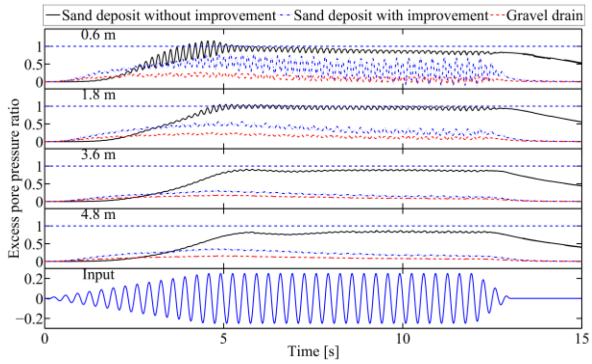

Figure 3. Time histories of excess pore water pressure at selected depth locations

Figure 4 shows these drag forces normalized by the weight of the particles at different depth locations. A normalized drag force value of one indicates that the fluid is essentially carrying the particles and the effective stresses would approach zero. In the deposit without improvement, the magnitude of the normalized drag force approached the value of one at all depth locations except near the base, indicating liquefaction has occurred at those upper depth locations. For the deposit treated with gravel drains, the vertical drag forces exerted by the fluid on the gravel and sand particles remained mostly within the submerged fraction of the weight of the solid particles, indicating liquefaction did not occur in the sand nor the gravel.

The computed horizontal acceleration time histories for the loose deposit are shown in Figure 5. The acceleration vanished for the top half of the loose deposit and maintained an amplitude close to the input base motion for the bottom half. Full transmission of the ground motion from the base rock to the surface can be observed for the deposit with the drain (Figure 6). The acceleration amplitude at the corresponding depth locations between the gravel and sand were comparable as the gravel drains results in a stiffening effect for the whole deposit. That is, the motion of the non-liquefied gravel dictated the lateral acceleration of the whole deposit.

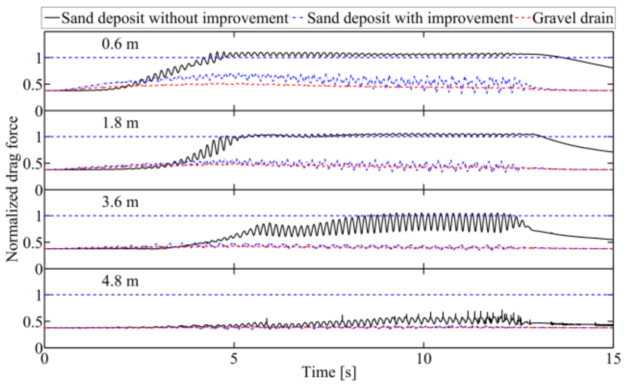

Figure 4. Time histories of vertical fluid drag force normalized by the average particle weight at selected depths

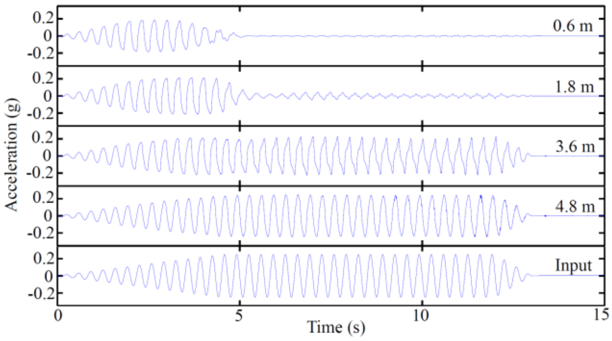

Figure 5. Time histories of average horizontal acceleration at the selected depths inside the loose deposit.

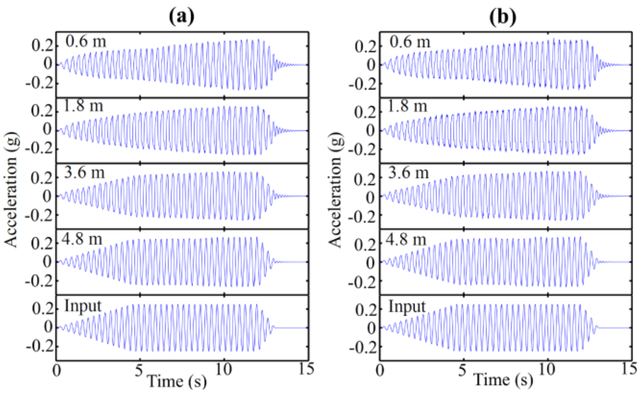

Figure 6. Time histories of average horizontal acceleration at selected depths: (a) inside the gravel drain, and (b) within the surrounding sand.

Liquefaction is a state of instability that is marked by vanishing effective confining pressure and shear stresses as well as the development of large strains. Figure 7 shows the shear stress-strains histories for the loose sand deposit. Significant reduction in shear stresses and stiffness was observed as well as shear strains approaching values as large as 0.7 %. In case of the deposit treated with gravel drains, the shear stress-strain loops indicated stiffness reduction and large shear strains at locations near the surface in both the gravel and sand portions of the deposit (Figure 8) without loss of strength. At deeper depth locations, the level of strains experienced by the sand were smaller than the case with no gravel drain treatment.

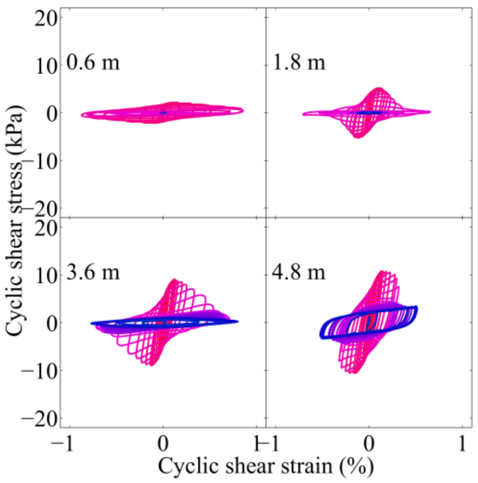

Figure 7. Shear stress-strain loops at selected depths (the loose deposit)

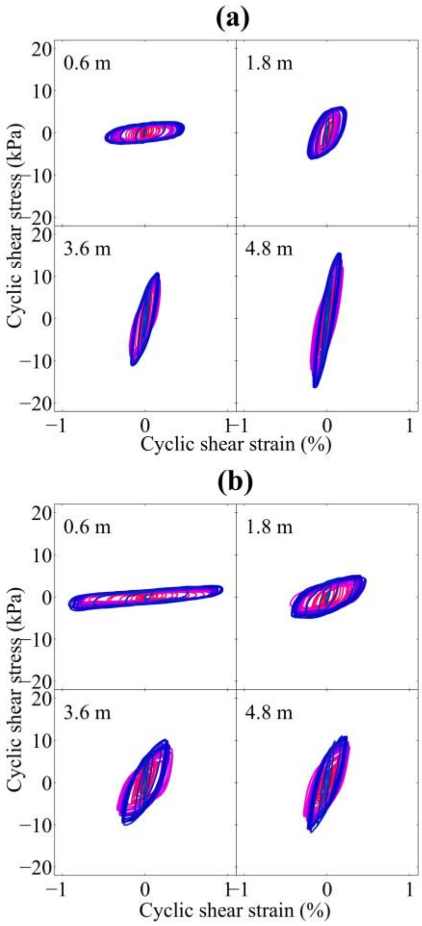

Figure 8. Shear stress-strain loops at selected depths: (a) inside the gravel drain, and (b) within the surrounding sand.

Plots of the effective confining stress paths at different depth locations for the loose deposit are shown in Figure 9. Significant reduction in mean confining pressure (completely vanishing in top levels) was observed. The effective stress paths at different locations along the treated deposit confirm that there was no loss of strength marked by values of effective confining pressure approaching zero (Figure 10).

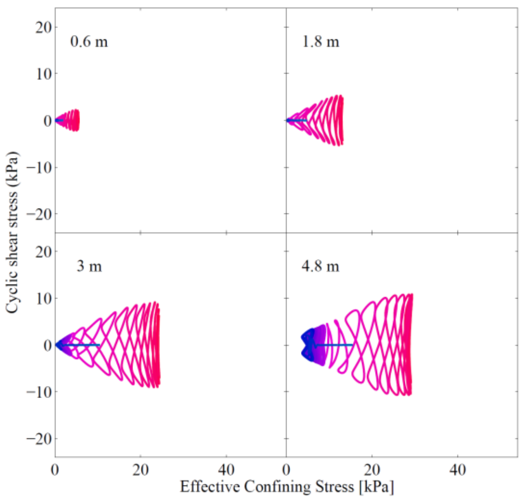

Figure 9. Time histories of effective stress path at selected depths (the loose deposit)

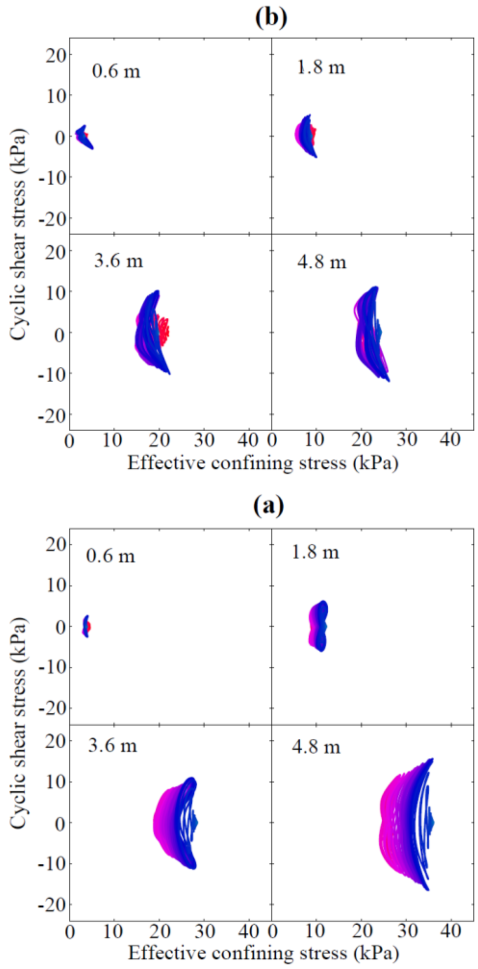

Figure 10. Time histories of effective stress path at selected depths: (a) inside the gravel drain, and (b) within the surrounding sand

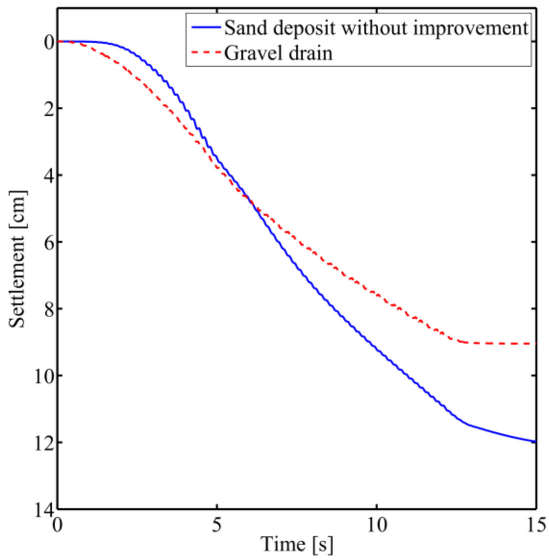

Figure 11. Time histories of surface settlement before and after installation of the gravel drain

The time histories of surface settlement for the loose deposit and at points near the surface of the drain in the improved deposit are provided in Figure 11. According to this figure, one could conclude that the overall settlement of the site has slightly improved compared to the untreated loose sand deposit (settlement reduced from 12.5 cm to 9 cm), since practically the foundation soil would be considered that of the gravel drains. However, this improved settlement magnitude still exceeds the acceptable limits by most code provisions.

4 CONCLUSIONS

A three-dimensional fully coupled particle-based model is presented to evaluate the dynamic response and liquefaction of saturated granular deposits as well as the use of gravel drains as a liquefaction mitigation measure. A microscale idealization of the solid phase is achieved using the discrete element method while the fluid phase is modeled using the smoothed particle hydrodynamics. The presented model is computationally far less demanding compared to the pore-scale level models and its meshless nature makes it a powerful tool for analyzing moving boundary, irregularly shaped domains, and free surface problems. A key feature of the employed technique is that it does not presume undrained conditions for the granular deposit and allows for spatial fluid movements within the deposit. The proposed approach was used to model the response of a loose deposit to seismic excitation and modeling gravel drains as a measure to mitigate liquefaction hazards. The loose deposit experienced liquefaction marked by several response mechanisms including excess pore-pressure buildup approaching the value of one, increase in the vertical drag forces that counterbalance the weight of solid particles, diminishing averaged particle acceleration time histories and continuous degradation of soil stiffness and strength. The installation of gravel drains effectively reduced pore-pressure buildup and for the most part the soil maintained its strength.

5 ACKNOWLEDGEMENTS

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