DEM Simulations of the Effect of Desaturation on Liquefaction Hazard Mitigation

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ABSTRACT

Earthquake-induced liquefaction is always a concern when the soil near the surface of a site is composed of relatively loose saturated sand. One of liquefaction mitigation methods is to induce gas bubbles into the deposit to reduce the degree of saturation. A coupled pore-scale model is presented herein to investigate liquefaction resistance of desaturated granular materials. The multiphase fluid, which mimics the behavior of air and water, is modeled using the multiphase single component lattice Boltzmann method. The solid phase is modeled using the discrete element method. The coupled framework is utilized to study the behavior of a soil deposit with gas bubbles-induced desaturation during an earthquake loading. Simulation results suggest that the risk of liquefaction effectively decreases with small reduction in the degree of saturation.

INTRODUCTION

Liquefaction occurs when the soil has lost its strength and behaves like a fluid. In this condition, the strength of soil drops below the level needed to remain stable. Throughout the cyclic loading, the saturated loose sand tends to densify, resulting in a buildup of pore water pressure as the void space reduces. The increase in pore-pressure causes particles contact forces to relax and eventually vanish, marking zero effective stress state and complete loss of soil strength.

Different site mitigation techniques have been developed to decrease the risk of liquefaction in saturated sands. One of the promising techniques is inducing gas bubbles to decrease the degree of the saturation to mitigate liquefaction risk. One of the advantages of such techniques is its feasibility to be used beneath existing facilities. Okamura et al. (2006) observed that the induced desaturation technique was an effective method to mitigate the risk of liquefaction and the desaturated condition can last for a long time, generally more than a decade. Yegian et al. (2007) used electrolysis to entrap gas molecules in saturated sand by ionization of hydrogen and oxygen. The other method utilized in their study was trapping air bubbles by draining the water from the bottom and reintroducing it from the top of the specimen. Yegian et al. (2007) conducted studies confirmed the desaturation technique not only as an efficient method to increase liquefaction resistance but also as a cost-effective technique in comparison with other methods.

In addition to the above mentioned experimental studies, numerical techniques have also been presented by researchers. Bian and Shahrour (2009) used cyclic elastoplastic constitutive model to study the effect of saturation on liquefaction potential in partially saturated soils. Buscarnera and Di Prisco (2013) used the material stability theory to investigate unsaturated slopes. They utilized a coupled hydromechanical constitutive model to study the onset of instability detected by different failure modes such as static liquefaction. Liu and Muraleetharan (2012) presented a constitutive model for unsaturated sands and sandy silts. They used the model to investigate the effects of the degree of saturation, relative density, initial state, and stress state on liquefaction during shaking.

The Discrete Element Method (DEM) effectively considers the discontinuous behavior of granular soils. DEM was introduced by Cundall (1971) for rock and granular material problems. Later, DEM was applied to soil mechanic problems by Cundall and Strack (1979). DEM uses Newton's second law and contact relationships to calculate motion and inter-particle contact forces. The Lattice Boltzmann Method (LBM) is a powerful technique for simulating the behavior of fluid systems. The key concept in LBM is considering the behavior of the group of molecules or atoms rather than every single one. LBM simplifies the Boltzmann equation by decreasing the number of particles and confining the particles position and their movement directions. One of the strengths of LBM is its ability to simulate the multiphase fluids with single and multi-components. This means, surface tension, evaporation, cavitation, and many other problems can be simulated by LBM. Shan and Chen (1994) developed a multiphase single-component model where an additional forcing term is added to the velocity field to produce the phase separation. Huang et al. (2009) utilized the multiphase single-component LBM to simulate the viscous coupling effects of two-phase flow in porous media. Eshghinejadfard et al. (2016) used multiphase single-component LBM to calculate the permeability by simulating laminar flows in porous media.

In this paper, results of soil-water systems with various degrees of saturation are presented based on a coupled pore-scale idealization of the pore-fluid and a discrete description of solid particles. The micro-scale representation of the solid phase is obtained using DEM, while the multiphase fluid is modeled at a pore-scale using single component LBM. The fluid forces applied to the particles are determined based on the momentum exchange between the fluid and particles. The introduced procedure is utilized to model the response of a soil deposit with various degrees of saturation subjected to seismic excitation. Results of the simulations show that a small decrement to the degree of saturation of a fully saturated deposit significantly impacts the magnitude of the excess pore pressure ratio.

COUPLED LBM-DEM APPROACH

A fully coupled model is presented herein to simulate granular deposits with various degrees of saturation subjected to a dynamic base excitation. The fluid is modeled at pore-scale using the LBM. The method of generating a multiphase LBM model introduced by Shan and Chen (1994) is utilized herein. The micro-scale response of the pack of solid particles is captured using DEM. In the LBM-DEM coupled model, there is a different time step for each of the phases. In this study, the DEM time step is defined to be smaller than the LBM time step. Therefore, a subcycling time integration for the calculation in the solid phase is required. In the coupled model, the fluid and momentum equations for each particle are solved using an explicit time integration scheme. The bounce-back fluid boundary condition is applied between the solid particle surface and fluid. Details of the employed model could be found in Nateghi and El Shamy (2020).

MODEL VERIVICATION

While there are several publications presenting the effects of desaturation on liquefaction mitigation through 1g and geotechnical centrifuge experimental results (e.g., Ghayoomi et al., 2011; Ravichandran et al., 2013; Mirshekari and Ghayoomi, 2017), current computational power does not make it practical to have a one-to-one comparison with those experiments. Therefore, verification simulations were performed before running the main model to ensure the LBM code and the coupled LBM-DEM code were without errors.

A spherical light fluid contained in a denser one, which forms a bubble, is affected by inward pressure and outward pressure. The inward pressure works to enlarge the bubble while the outward pressure squeezes it. The surface tension acts as a counterbalancing force to hold the bubble at a constant size. Based on Laplace law, the relationship between the inside and outside pressure difference (ΔP) and ($1/r$) is a straight line with zero intercept, where the slope of the line represents surface tension. By simulating series of bubbles with different radius sizes, surface tension can be estimated. Three-dimensional models were generated with periodic boundaries. In these models, denser fluid, which represents the surrounding phase, is 20 times heavier than the embraced fluid. Figure 1 presents the plot of ΔP vs. $1/r$ and shows that the model follows Laplace law.

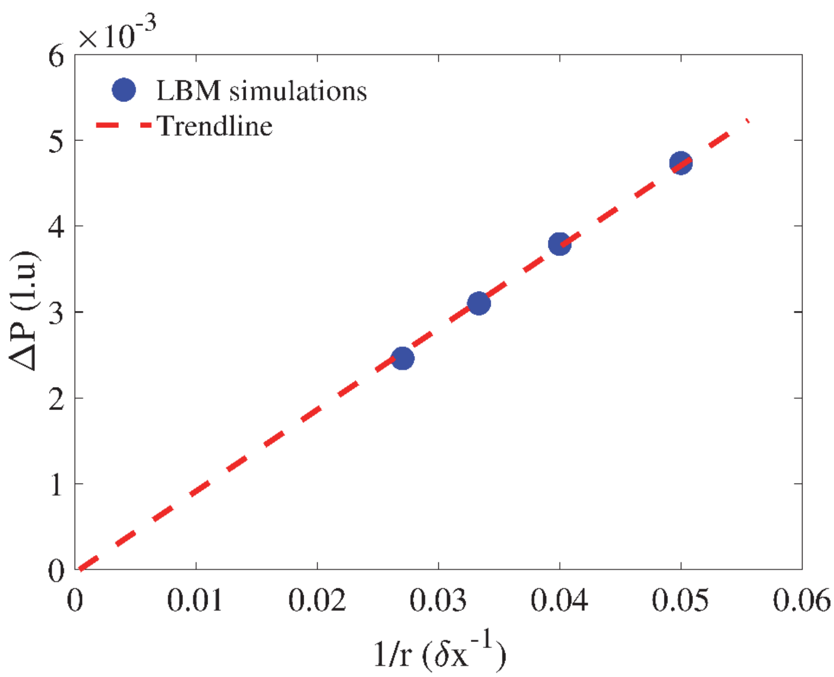

Figure 1. Linear relation between the pressure difference and the inverse of radius for estimating the surface tension (l.u represents the lattice units).

SIMULATIONS

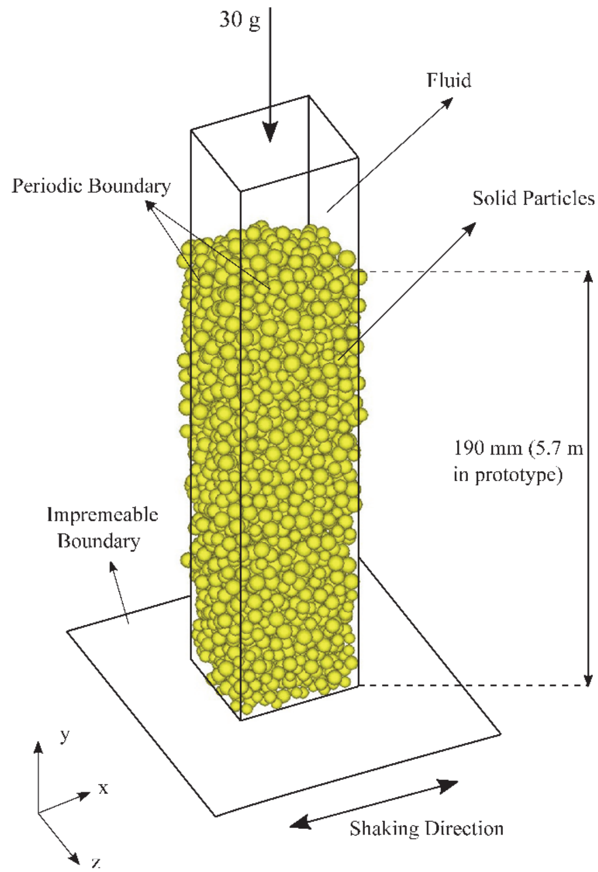

Figure 2. 3D view of saturated granular deposit.

Three granular deposits with different degrees of saturation were generated to examine the behavior of desaturated soils subjected to an applied shaking. A one dimensional dynamic base excitation in the x-direction was applied to the deposit shown in Figure 2. To model an infinite system, periodic boundary conditions for both the fluid and solid phases are set at the lateral boundaries (El Shamy and Abdelhamid, 2014). Periodic boundary conditions make it possible to simulate the massive problem in a limited computational domain. The lower boundary is simulated as an impermeable boundary for both phases. In the solid phase, the base wall mimics the behavior of a solid wall that can move in a horizontal direction. In the fluid phase, the bounce-back boundary condition is used to simulate the solid wall behavior. The constant pressure boundary condition is utilized to mimic the fluid surface. A semi-infinite deposit was generated by particles that are falling under gravity force in a parallelepiped domain with periodic boundaries in lateral directions. The granular deposit was generated using the submerged density of the soil to consider the buoyancy effect on the particles.

To decrease the number of particles in DEM, the number of nodes in LBM and the duration of the applied shaking, a high gravitation acceleration was applied to the model. The applied high-g level mimics the small scale geotechnical models in centrifuge testing conditions. This method was found to be a useful technique in DEM simulations to decrease the computational domain to a manageable size in several applications (e.g., El Shamy et al., 2010; El Shamy and Aydin, 2008). A summary of computational parameter details and proprieties for particles and fluids are listed in Table 1.

Table 1. Simulation parameters.

Particles	
Diameter	4.8 mm - 7.2 mm
Normal stiffness	5×10^6 N/m
Shear stiffness	5×10^6 N/m
Normal damping ratio	0.1
Shear damping ratio	0.1
Friction Coefficient	0.5
Density	1650 kg/m^3
Number of particles	3100
Fluid	
Density	1000 kg/m^3
Viscosity	5.0 Pa.s
LBM nodes number	$103\times480\times103$
G	-5.2
Computation parameters	
g-level	30
LBM Time step	8×10^{-6} s
DEM Time step	8×10^{-7} s

In the conducted simulations a 190 mm high deposit of particles with lateral dimensions of 50 mmx50 mm was generated. Particles had an average diameter of 6 mm with a minimum diameter of 4.8 mm and a maximum diameter of 7.2 mm (Fig. 2). The applied high gravitational acceleration to the granular deposit was 30g. Based on the centrifuge scaling laws, the macroscopic length and time scales in the model were 30 times smaller than those in the prototype. Correspondingly, the acceleration amplitude and motion frequency in the model are 30 times larger than those in the prototype. The model resembles a prototype where the depth of the granular deposit is 5.7 m.

One dimensional dynamic base excitation (in the x-direction) was applied as a velocity time history to the solid base wall on which the particle deposit was resting. The sinusoidal acceleration input signal gradually increased until reaching the maximum amplitude at 4.5 s. Then it remained constant for an extra 7.5 s and gradually decreased to zero at 13 s. To estimate the low strain shear modulus, the average shear wave velocity, and the natural frequency of the fully saturated deposit, a sinusoidal base acceleration with an amplitude of 0.01g and a frequency of 3 Hz was applied to the deposit under a 30 g gravitational acceleration. The average low strain shear modulus is 70 MPa, the average value of shear wave velocity is about 187 m/s, and the natural frequency of the deposit is about 8.2 Hz. The results of models with 100%, 92%, and 82% of the degree of saturation were analyzed. Results are presented herein in prototype units unless otherwise specified.

Excess pore pressure ratio (ratio of pore-fluid pressure increment to initial vertical effective stress) and effective stress time histories were used to identify liquefaction from a macro-scale perspective. Buildup of excess pore-pressure ratio was the essential factor to identify the starting point of liquefaction. Generally, liquefaction was defined as the moment at which the excess pore-pressure ratio reaches a value of one. At this moment, the inter-particle contact forces approached zero and consequently, the effective stress vanished. The time histories of the excess pore-pressure ratio at selected depth locations for the models with different degrees of saturation are shown in Figure 3.

The results show that the pore pressure ratio approached values between 0.8 and 1 at the upper 2.7 m of the fully saturated deposit. At the deeper locations of the fully saturated deposit, excess pore pressure ratio remained around 0.8. Based on the conducted simulations, liquefaction occurred at the fully saturated deposit. In the desaturated deposits, despite the increase of the excess pore pressure ratio at shallow depth locations, this ratio remained below 0.5 for all levels (Fig. 3). Liquefaction was not observed at any depth in the 82% and 92% saturated deposits. It can also be concluded that the decrease in the degree of saturation from 100% to 92% has a significant effect on excess pore pressure ratio decrement. However, further decrement of the degree of saturation from 92% to 82% has less sensible impact. This response shows that a small percentage of decrement in the degree of saturation has a significant effect in mitigating the risk of liquefaction.

CONCLUSION

This paper examines the potential of a developed three-dimensional pore-scale model to analyze liquefaction in fully and desaturated granular deposits during seismic excitation. The multiphase single-component lattice Boltzmann method was used to model the fluid phase at the pore-scale while the solid phase was idealized at the micro-scale using the discrete element method. The presented LBM-DEM coupled model considers the discrete behavior of the granular particles, including the real flow of fluid in pore space. The forces applied to the particles by fluid-phase were computed by considering the momentum exchange between the particles and fluid. The model was utilized to simulate the response of soil deposits with different degrees of saturation during seismic excitation. Three granular deposits subjected to a dynamic excitation with 100%, 92%, and 82% degrees of saturation were modeled. Based on the results of the conducted simulations, liquefaction occurred in the fully saturated granular deposit. For the same set of conditions that were applied for the fully saturated deposit, liquefaction was not observed at any depth location of the desaturated deposits. It was also noticed that the reduction of the degree of saturation from 100% to 92% impacts the behavior notably. In the depth location close to the surface, excess pore pressure ratio dropped from a value close to 1 to less than 0.4. Also, in deeper points of the 92% saturated deposit, a significant drop in the excess pore pressure ratio was observed in comparison to the values observed in the fully saturated deposit. The next level of decrement in the degree of saturation from 92% to 82% does not have a significant effect on the computed excess pore pressures.

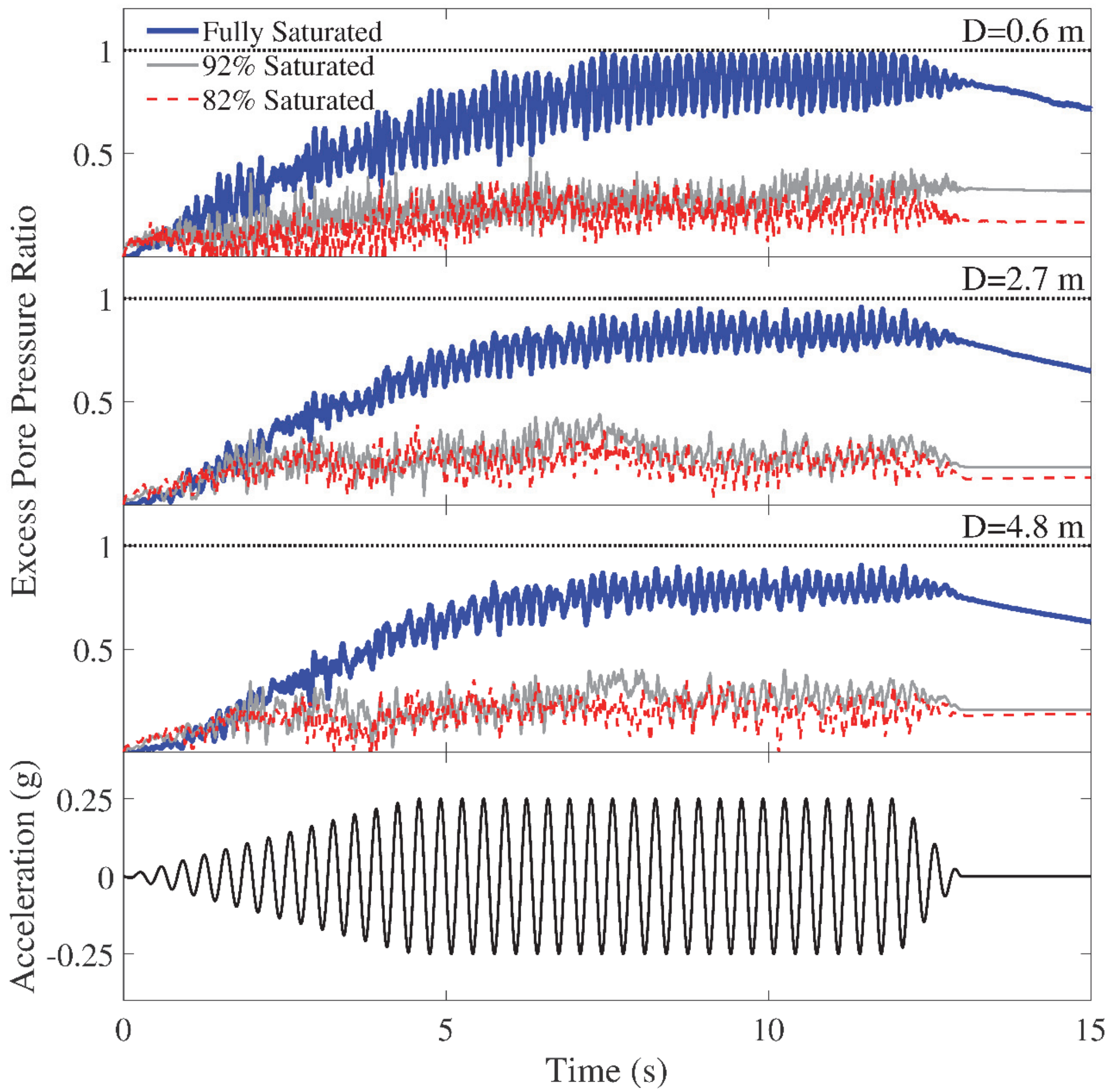

Figure 3. Time histories of excess pore water pressure at the selected depths.

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