The 2013 World Congress on
Advances in Structural Engineering and Mechanics (ASEM13)
Jeju, Korea, September 8-12, 2013

Vorticity-induced Lateral Force Mechanism and Onset of Local Flow Instability in Quicksand

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ABSTRACT

The onset of instability of fluid flow breaking through dense particles in quicksand was studied. Noticeable lateral migration was found and a novel vorticity-induced lateral force mechanism was proposed to explain the onset of local flow instability. A two-phase numerical simulation tool was adopted that consists of discrete element and lattice Boltzmann methods. A thin rectangular box was modeled in which 3000 mono-sized solid spheres are randomly packed and filled with Newtonian liquid. Constant pressure was imposed on the top and bottom surfaces to create an upward pressure gradient. The occurring of quicksand was validated with the simple effective stress estimation from soil mechanics. Detailed particle-fluid interaction was studied to reveal the onset of fluid flow breaking through the local packed structure. We observed that at the beginning of quicksand simulation, pressure-induced upward flow was blocked and trapped by local dense-packed particles. Then the vorticity field from fluid induced lateral forces to move nearby particles in the lateral direction of the stream. Consequently, the lateral motion of particles loosened the local dense pack and triggered the local flow instability. The propagation of pores finally resulted in the quicksand condition.

1. INTRODUCTION

Quicksand is a classical phenomenon in geotechnical engineering (Das 2008), which is used to study the effect of pore water in the porosity media. Generally speaking, quicksand is a condition that the saturated soil loses stiffness to bear the additional stress. This condition is usually induced by the upward-flowing fluid. Since soil behaves as it is boiling under such condition, quicksand is also known as sand boiling. The quicksand phenomenon is commonly observed and has been extensively studied in laboratories. Recent advances on solid-fluid interaction modeling provide an opportunity to predict the phenomenon quantitatively and to elucidate the causes responsible for phenomenon. Zeghal and Shamy (2008) studied the soil liquefaction by using the coupling of discrete element method (DEM) and average Navier-Stokes equations simulation. They showed that the two-phase numerical scheme could reproduce phenomenon of quicksand, and found that large pressure will lead to boiling state in quicksand, which can be considered as a transition of soil bulk to a suspension. Mansouri (2008) Also, the two-phase numerical simulation for quicksand was achieved by, M. (2008), used three dimensional lattice Boltzmann method for modeling pore fluid and discrete element method for particle to simulate quicksand condition. He found that the critical hydraulic gradient of boiling state from simulation is consistent with the simple effective stress estimation used in soil mechanics.

Despite these modeling efforts, physical mechanisms that trigger the onset and propagation of pores in quicksand remain unknown. Conceptually, upward seepage trivially lifts solid particles up and it is not clear how fluid beaks the packing of particles and consequently results in quicksand condition. In this work, we aim to elucidate these mechanisms. A solid-fluid coupling simulation is used to capture detailed interaction between pore fluid and porosity media constructed by the particles. Saffman's lift force (1964) will be introduced to explain how fluid breaks the bulk structure by means of lateral effects on particles.

2. Quicksand Modeling

The solid-fluid scheme is composed of the discrete element method (DEM), lattice Boltzmann (LB) and immersed boundary methods (IBM). The discrete element method models particle collision and dynamics via the contact theory and Newtonian dynamics. The lattice Boltzmann method provides an effective mean to capture dynamics of fluid. The immersed boundary method describes the interaction between fluid and solid. For quicksand modeling, a thin rectangular box shown in fig. 1 was modeled in which 3000 mono-sized solid sphere were randomly packed to two-thirds of the box height in Newtonian fluid. The box was 0.25 m, 0.3 m and 0.05 m in width, height and thickness, respectively. In order to characterize pore fluid in details, the model contains a high-resolution fluid mesh with more than 3 million structured lattice Boltzmann elements. Each particle in the box was 0.001 m in radius, 2.65 kg/m^3 in density. For simulating fluid seepage, the pressure boundary conditions of fluid at top and bottom were set; the top side is equivalent to the free surface of fluid and air, and the bottom side is set with a higher pressure value to form a pressure gradient from the bottom toward top surfaces.

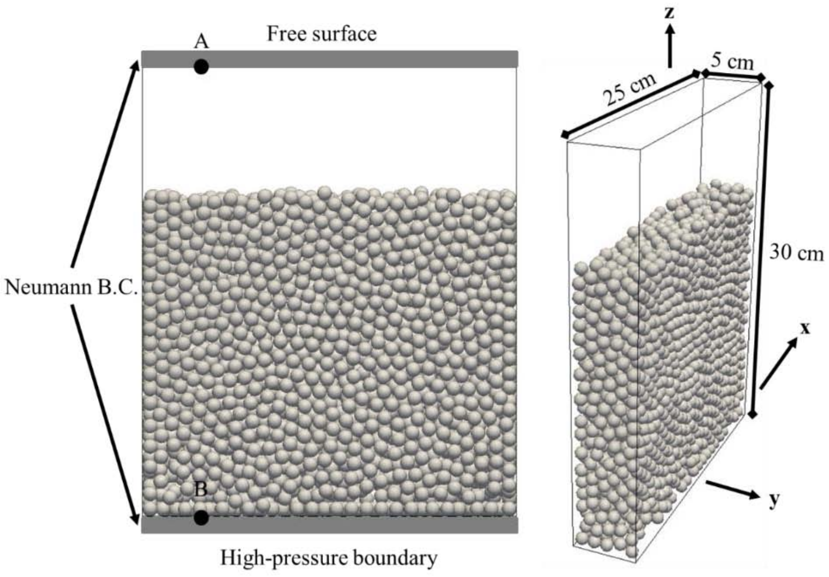

Fig. 1 Illustration of quicksand model.

3. Results and Discussion

3.1 Occurrence of quicksand

Figure 2 shows the profile of normalized effective stress and vertical position of bulk strata in a quasi-steady state. With increase of prescribed hydraulic gradients, the effective stresses show tendency toward the quicksand condition. When the hydraulic gradient is 0.450, particles retain enough effective stress to sustain the bulk skeleton. As the hydraulic gradient increases, the effective stresses decreases and almost vanishes when hydraulic gradient is equal to the critical hydraulic gradient (0.981) found from classical estimation from soil mechanic. Vanishing effective stresses along the depth thus indicates the occurrence of quicksand.

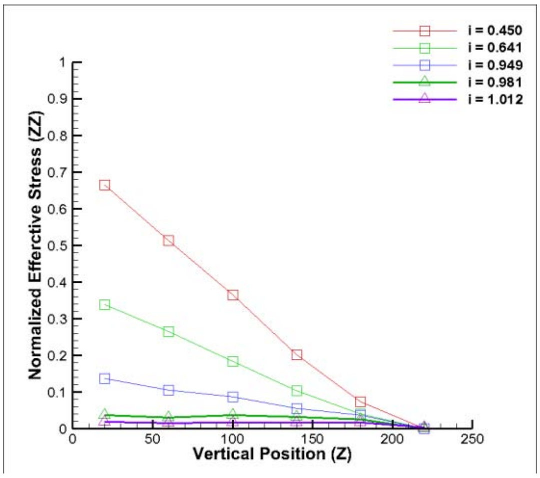

Fig. 2 Steady-state effective stresses subjected to different hydraulic gradients.

3.2 Microscopic observation of onset of quicksand

At the beginning of quicksand, flowing fluid will be blocked from dense-packed particles. Thus fluid is not able to flow along the pressure gradient. For releasing the sustained normal stress, local fluid has to find another gap to go through this porous medium. Hence, the fluid will either make a conductive motion in gaps of particles or have nearby particles move. Nevertheless, fluid is already blocked from flowing along pressure gradient, the fluid has to move nearby particles laterally. In order to explain the particle lateral migration caused by fluid flow, the shear-induced lift force is consequently introduced to describe this effect. Saffman (1964) proposed a “lift” force $\mathbf{F}_L$ to quantify a lateral effect of fluid:

$$\mathbf{F}_L = K r^2 \sqrt{\nu}\left(\mathbf{u} \times \boldsymbol{\omega}\right), \tag{1}$$

where K is the lift force coefficient, r is the particle radius, ν is kinematic viscosity, $\mathbf{u}$ is relative velocity of particle and fluid, and $\boldsymbol{\omega}$ is fluid vorticity. Since the force is the resultant of shear stress of fluid, Saffman’s lift force is also known as shear-induced lift force. Physically, Eq. (1) indicates a particle in a shear fluid field will be subjected to a force perpendicular to the velocity direction of fluid flow. We note that different from the

Magnus effect, Saffman's lift force is induced by fluid vorticity, and is not related to rotation and motion of the particle.

Figure 3 plots the lateral velocity of particles undergoing upward fluid flow. The red arrow indicates particles that have a higher horizontal velocity, and the dashed half ring contains a regiment of particles. These particles are constrained in the vertical axis because of the packing; pore fluid can only move those particles laterally. Once a gap from particle lateral movements is formed, fluid can upwardly flow with through the gap then move to another pore between particles. Figure 4 depicts the lift force variants. Lift forces along the horizontal axis are remarkable large near the observed particle. It is therefore confirmed that the shear-induced lift force causes lateral migration of particle and is responsible for the onset of pore propagation.

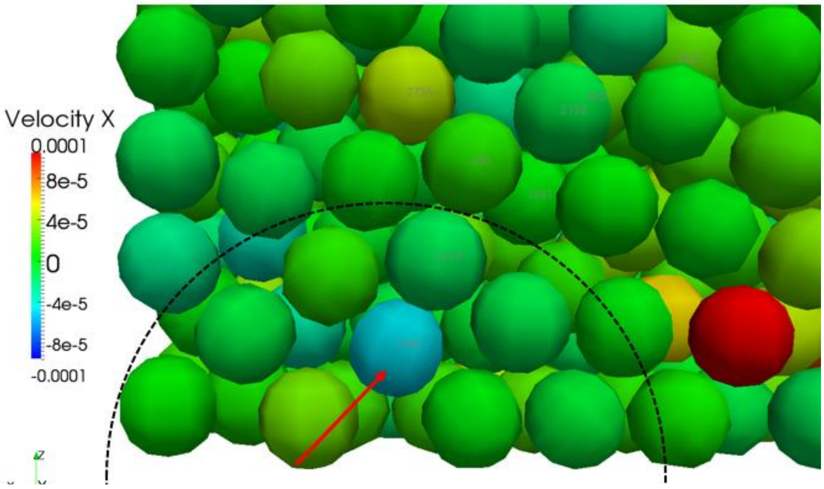

Fig. 3 Particle configuration at bottom-left corner with velocity in x-axis at 3.5 s

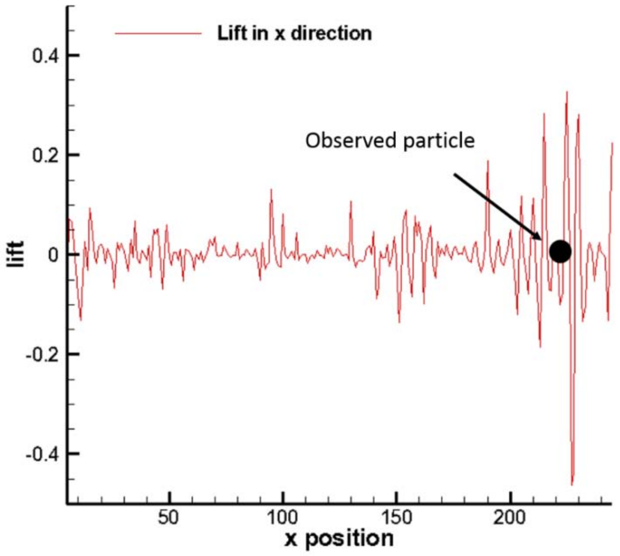

Fig. 4 The observed particle with lift distribution along x axis at 3.5 s.

3. CONCLUSIONS

A two-phase solid-fluid coupling simulation tool composed of DEM, LBM and IBM was developed. The classical quicksand condition and its mechanisms were studied. We found that the onset of pore propagation was caused by lateral motion of particles where the lateral motion was the consequence of the vorticity fluid field. Saffman’s lift force was calculated to further support the vorticity-induced onset mechanism.

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