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DEM-PFV Analysis of Solid-fluid Transition in Granular Sediments under the Action of Waves

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Abstract. Solid-fluid transition is a very active area of investigations. It is linked to many applications in geomechanics and near-shore or off-shore engineering. Micromechanical models can give useful insight into the governing mechanisms of this phenomenon, provided they can reflect the role of pore fluids accurately. We present the application of a new hydromechanical model, combining the Discrete Element Method (DEM) to a flow model based on a pore-scale discretization in finite volumes (PFV) for incompressible pore fluids, to simulate the response of near-shore granular sediments subjected to the action of stationary waves. The model reproduces a wide range of physical processes observed in the experiments, including temporary liquefaction events.

Keywords: Discrete Element Method, Hydromechanical Coupling, State Transition, Liquefaction
PACS: 43.35.Ei, 78.60.Mq

INTRODUCTION

The integration of fluid-grains interactions in discrete particle models has been the object of very active researches in the recent years [1] [2]. We developed recently a new method for the simulation of hydromechanical couplings, linking the discrete element method (DEM) in 3D to a Pore-scale Finite Volume (PFV) scheme [3], which has potential applications for natural as well as industrial granular media. In the first section of this paper, we summarize the governing equations of the DEM-PFV coupling. In the second part we present the application of the model to the analysis of the deformation and wave-induced liquefaction of granular sea bed sediments.

This application points out the potential of the DEM-PFV coupling in the study of state transitions. More specifically, the DEM-PFV model appears as a promising type of coupling for its ability to handle strong poromechanical couplings and liquefaction at a reduced computational cost [3] [4].

NUMERICAL MODEL FOR SATURATED GRANULAR MATERIALS

The Coupled DEM-PFV Model

We employ here the DEM in 3D, with elastic-frictional contact and explicit time integration, as implemented in the opensource code Yade-DEM [5]. In the belief that the reader already knows the basics of the numerical scheme of DEM, a priority is given to the coupling of this method with the Pore-scale Finite Volume (PFV) numerical scheme for the resolution of the flow problem. For a detailed derivation, the reader can refer to Chareyre et al. [3].

The PFV model is based on a partition of the pore space, which is obtained by constructing the regular triangulation [6] of the packing (Fig.1A). A system of tetrahedra, with spheres at each vertex (Fig.1C), arises, each one representing what we call hereafter a *pore*. A finite volume formulation for Stokes flow between adjacent pores is made possible by such discretization. Dual to the triangulation, the Voronoi tessellation system (Fig.1B) defines the connections between adjacent pores. At this scale, one can relate the flux q_{ij} between connected elements i and j to the local pressure gradient and the pore-space geometry. The relation can take the form of a generalized Poiseuille law defining the local hydraulic conductivity k_{ij}, as introduced in [3] and verified experimentaly in [7]. In the case of full saturation by an incompressible fluid, the rate of volume change of one pore is equal to the sum of four fluxes q_{ij} through the facets of the element. This finally links the rate of volume change of the element (itself function of particles velocity) to the pressure field p_k:

$$\dot{V}_i^f = \sum_{j=j_1}^{j_4} q_{ij} = k_{ij}\frac{p_i - p_j}{l_{ij}} = K_{ij}(p_i - p_j) \qquad (1)$$

Writing this equation for all elements defines an implicit problem that has to be solved at each time step of a simulation to determine the pressure field. The forces exerted by the fluid on each particle can finally be derived with the help of a momentum conservation equation. Three terms appear in the force, which are contour integrals of the hydrostatic pressure $\rho g z$ (buyoancy force), of the

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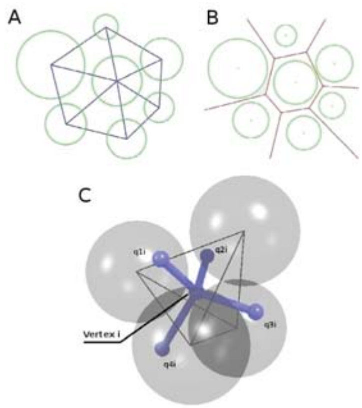

FIGURE 1. The PFV geometrical scheme. (A) 2D view of regular triangulation. (B) 2D view of tessellation. (C) 3D view of a pore and its connections.

piezometric pressure p^* and of the viscous shear stress tensor τ, respectively:

$$F^k = \int_{\partial\Sigma_k} \rho\, g\, z \mathbf{n} ds + \int_{\partial\Sigma_k} p^* \mathbf{n} ds + \int_{\partial\Sigma_k} \tau \mathbf{n} ds \qquad (2)$$

with $\mathbf{n}$ the unit normal of the contour.

These forces can be integrated into the explicit time-stepping algorithm of the DEM by summing them with the contact forces. The rate of volume change of the pores is computed at each time step, then the system defined by eq.(1) is solved to obtain the pressure field, and new forces are computed for the next step according to eq.(2). Taken as a whole, the coupled scheme is semi-implicit.

SEDIMENT HYDRODYNAMICS

The PFV-DEM model was successfully applied to the simulation of a consolidation problem (i.e. oedometer test) [4]. Here we present the application of the model to the simulation of the response of near-shore granular sediments subjected to the action of stationary waves, as inspired by recent experiments by Michallet et al. [8]. The instability induced by cyclic loading associated to the action of waves and the influence of an initial state condition such as porosity, will be commented.

Our simplified modeling of the waves action is based on a sinusoidal-shaped pressure condition at the top boundary of the packing: $p = p(x) = A cos(x/L)$, with L the length of the domain and A the amplitude.

As shown on fig.2, a half period is considered, with a condition of symmetry on lateral boundaries of the sample, and an impermeable bottom boundary.

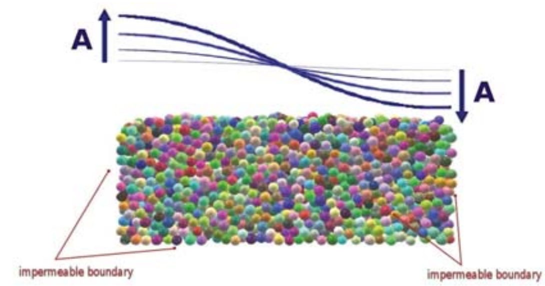

FIGURE 2. Representation of the wave action, boundary conditions.

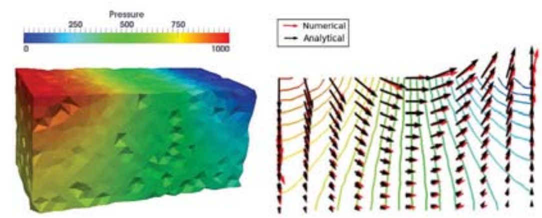

FIGURE 3. Wave simulation - (A) Pressure field (half period) with $A = 500$Pa and (B) velocity field and equipotential lines compared with the analytical solution of an equivalent Darcy's problem.

Fig.3(A) shows the pressure field that was obtained numerically over a 3D sample with $A = 500$Pa. Fig.3(B) compares directly the numerical and the analytical solution (Darcy's flow through a continuum medium), in terms of equipotential lines and velocity field, that are found in good agreement.

Standing Wave Simulation

A first series of simulation is performed with a wave amplitude A (see Fig.2) increasing linearly with time: $p = p(x,t) = A(t) sin(x/L)$, $A(t) = A^* t$. Although such time evolution is not realistic, it lets one exhibit basic mechanisms of importance in the response of the sediment. Two situations are considered, differing in the value of initial porosity of the granular medium; we will refer henceforth to the loose case ($n = 0.436$) and the dense case ($n = 0.368$).

The results that were obtained are summarized in the graph of fig.4. The amplitude A of the wave, at which a significant variation of the kinetic energy of the system is observed, is much lower in the loose than in the dense case. Looking at the pressure fields, on fig.5, it can be seen how in the case of the loose sample, the pressure field deviates strongly from the one that would correspond from the boundary conditions that were specified,

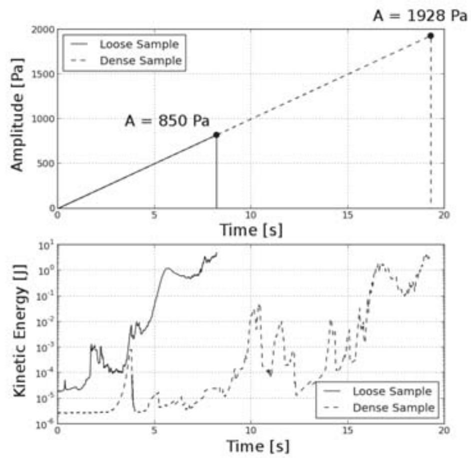

FIGURE 4. Wave action on a dense ($n = 0.368$) and a loose ($n = 0.436$) seabed. Amplitude and kinetic energy evolution.

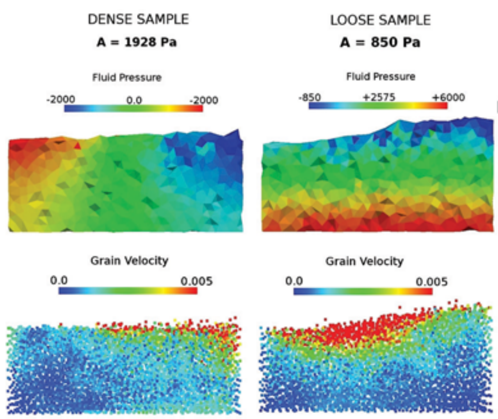

FIGURE 5. Pressure fields and deformation patterns corresponding to a condition of instability for the dense (A) and the loose (B) seabeds.

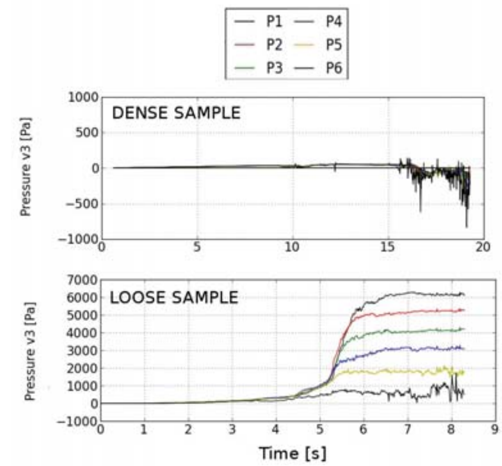

FIGURE 6. Pressure measurements along the symmetric axis of the dense and the loose seabeds (six equally spaced sensors, P1 the lowest, P6 the highest).

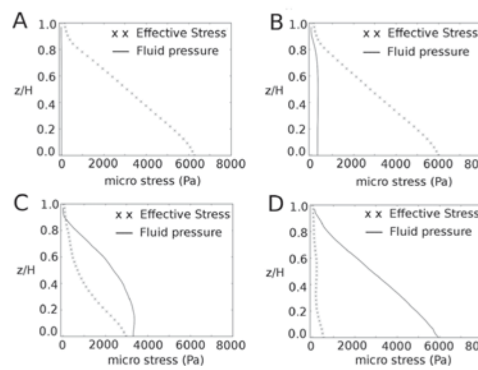

FIGURE 7. Loose seabed - Evolution of the fluid pressure and the effective stress profiles during the simulation.

which is not the case for the dense sample. The deformation patterns are also qualitatively different: the loose sample undergoes to a significant shear deformation.

On fig.6, pressures along the vertical axis $x = L/2$ are plotted for the two scenarios. We see that, differently to the dense case, where the pressures are close to zero, reflecting the boundary conditions that were specified, the pressure profile in the loose case exhibits an overall overpressure, which can reduce the shear strength of the seabed. We have confirmation of this idea by looking at the evolution of the microscopic effective stress, evaluated along the height of the initially loose sample, during the simulation. Fig.7 shows four snapshots of the simulation: the fluid pressure and the effective stress evolve as two complementary quantities (A-B). The progressive increase of the fluid pressure entails the progressive cancellation of the effective stress (C), which goes to zero in the last part of the simulation (D), resulting in a complete liquefaction of the medium.

Stationary Wave Simulation

In order to simulate a more realistic action of the wave, the next series of simulation define the pressure at the surface of the sediment as resulting from a stationnary wave: $p = p(x,t) = A_0 sin(t/T) sin(x/L)$, oscillating in time with period T. We show the result that was obtained on the loose sample ($n = 0.436$) by choosing a period of oscillation of $T = 1s$, within an amplitude $A_0 = 150$ Pa

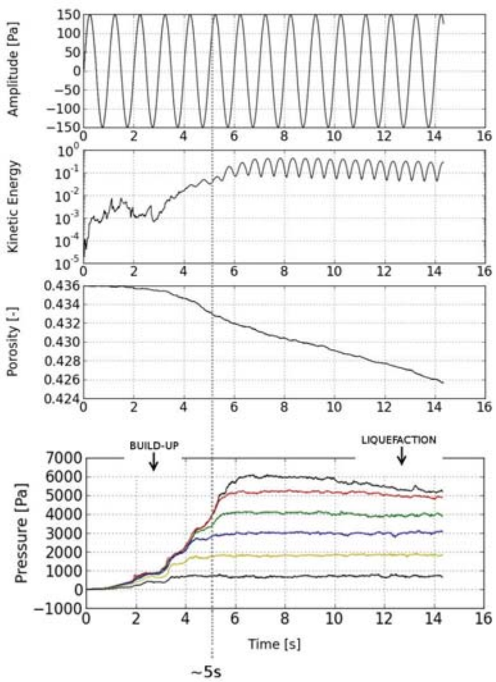

FIGURE 8. Stationary wave - Build-up liquefaction.

(see top plot on Fig.8).

Looking at the evolution of the kinetic energy and porosity, two phases can be easily distinguished. A first one (pressure buil-up), for $t < 5$s, corresponding to very small movements and a slight decrease of the porosity. A second one (liquefaction), for $t > 5$s, during which the reduction of the porosity becomes more important, and the kinetic energy gives evidences of larger deformations. As indicated by the evolution of pore pressure, the second phase corresponds to a liquefied state. This is the consequence of the progressive build-up of pore pressure during the first cycles of the simulation. By inspecting the velocity field (not displayed here), we found that the deformation corresponds to horizontal oscillations of a semi-circular zone of the sediment (similar to the moving zone in Fig.5 / loose sample), with a period equal to T.

CONCLUSIONS

An application of the DEM-PFV coupling to the analysis of the hydrodynamics of a granular sediment has been briefly presented. This first set of simulations allowed us to access some informations on the behavior of a model sediment subjected to the action of waves. The influence of the initial density on the response of the system has been first evidenced in the case of a standing wave. In the loose case, the sediment liquefies and undergo large deformations for a moderate wave's amplitude. In the dense case, it is stable for higher amplitudes and shows only superficial movements of particles near the sediment-water interface. The evolution of the pore pressure in the two cases is completely different. In the dense sediment, the pressure field is dominated by the boundary conditions (imposed pressure), and corresponds to a permanent flow regime weakly coupled to the movements of the particles. In the loose sediment, the pressure field is strongly modified by the deformation of the sediment. The pressure increases until the sediment reaches the situation of a complete liquefaction, as a result of strong poromechanical coupling. This first series of simulations was useful to validate the use of the PFV-DEM model for phase transition problems. It was shown it the last part (stationnary wave) that a progressive build-up of the pore pressure is obtained when the true nature of waves is accounted for via cyclic boundary conditions. This preliminary study shows that the governing mechanisms leading to the instability of sea-bed sediments are correctly captured by a DEM-PFV coupling. This is a promising first step toward quantitative analysis of the sediments response in realistic wave conditions.

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