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Coupled DEM-SPH Modeling of Saturated Sand

Y. Khalili, A. Mahboubi*, M. Haji-Sotoudeh

Department of Civil and Environmental Engineering, Shahid Beheshti University, Tehran, Iran

ABSTRACT: DEM (Discrete Element Method) is a particle-based method for modeling the granular materials. SPH (Smoothed Particle Hydrodynamics) is also a particle-based method to analyze fluids using a limited number of integration points. These mesh-free methods are suitable to analyze geotechnical problems with large deformations or complicated geometries. Coupling DEM and SPH for simulating multi-phase media, resolves the need for the spatial mesh and prepares a more realistic understanding of the saturated granular materials. In this study by coupling both DEM and SPH methods, a novel DEM-SPH model was developed to simulate saturated granular media such as saturated sand. The particles were modeled using DEM and the inter-particle fluid was simulated using SPH. The fluid flow and the particle-fluid interactions were included in the model. The model was validated by comparing the numerical results to experimental data. The evolution of the fluid pressure distribution was investigated. Three phases were observed in fluid pressure distribution. After starting loading, a pressure wave appeared adjacent to the top wall that formed a “transient phase”. After finishing the transient phase, a “stable phase” of the fluid pressure distribution started, during which the pressure gradient changed gradually. There was an “instable phase” at large axial stains. The pressure gradient changed randomly in this phase. The results showed that the model could satisfactorily predict the undrained behavior of the saturated granular materials and capture the local parameters of the inter-particle fluid e.g. the local variations of the fluid pressure.

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1- Introduction

DEM[1] is a particle-based method for modeling granular materials. The original DEM can only model assemblages of the dry particles. For modeling a medium consisting of the particles and the inter-particle fluid, it is needed to simultaneously solve the governing equations of the solid and fluid phases. SPH[2] is one of the recent methods used to solve the fluid governing equations. The key feature of SPH compared to the conventional CFD[3] is being mesh-free. Coupling DEM and SPH for simulating multi-phase media, resolves completely the need for the spatial mesh and prepares a more accurate understanding of the saturated granular material behavior compared to the DEM-FVM[4] models. The DEM-SPH models are compatible with large deformations, deformable boundaries, and irregular shapes of the medium.

Mogami [1] introduced the idea of considering sand as discrete particles for analyzing its behavior. Cundall [2] developed DEM and Cundall and Strack [3] used DEM for modeling soils. Gingold and Monaghan [4] and Lucy [5] developed SPH for using it in astrophysics.

Numerous studies were performed by researchers to couple DEM and SPH. However, until now, there is no satisfactory coupled DEM-SPH model for simulating the undrained behavior of the saturated granular materials under undrained loading, e.g. undrained triaxial shear tests on saturated sand. The main reason is that the majority of the coupled DEM-SPH models developed in the literature used the weakly compressible formulation and did not account for the incompressibility of the pore fluid, which is a key factor that governs the undrained response of the saturated granular material. Furthermore, the undrained simulations of the granular materials were performed using extremely idealized models or with unrealistic assumptions. In this study a novel coupled DEM-SPH model is developed to more realistically simulate the undrained behavior of sand.

2- Solid Phase

The physical problems related to the motions and the interactions between particles, can be directly simulated using DEM. The DEM calculation cycle consists of applying Newton’s second law to the particles and the force-displacement law at the contacts.

Newton’s second law is used to determine the motions of each

1 Discrete Element Method
2 Smoothed Particles Hydrodynamics
3 Computational Fluid Dynamics
4 Finite Volume Method

*Corresponding author’s email: a_mahboubi@sbu.ac.ir

particle, and the force-displacement law is used to calculate the contact forces. In the DEM simulations, the local non-viscous damping is applied for the stability of calculations. This type of damping is similar to that mentioned by Cundall [6].

Many non-angular particle shapes can be modeled using overlapping spheres. In this study, particles consisting of two attached spherical particles with a predefined overlap ratio are used in the simulations.

3- Fluid Phase

The fluid governing equations including the momentum and continuity equations are commonly referred as Navier-Stokes equations. The locally averaged Navier-Stokes equations are derived by Anderson and Jackson [7]. In this study, the fluid governing equations are solved using SPH. SPH is an interpolation method in which using a limited number of integration points, the continuum parameters are approximated. The integration is performed by use of kernels which approximate functions. In the numerical work the integral interpolant is approximated by the summation interpolant.

The fluid viscosity in the SPH formulation is defined as the artificial viscosity. This term is applied in the momentum equation according to the suggested approach of Monaghan [8]. The interaction forces are calculated using the equation presented by Sun et al. [9].

In this study, the fluid pressure is calculated through the following steps. This procedure combines the equation of state, the incompressible fluid formulation and the constant volume conditions.

- Calculating a virtual pressure distribution using the equation of state,
- Performing the SPH flow calculations,
- Calculating the pressure gradient by having known the flow distribution,
- Determining the average fluid pressure to satisfy the constant volume conditions (the servo control algorithm), and
- Calculate the total pressure distribution by having known the average pressure and the pressure gradient.

4- Results and Discussion

The developed DEM-SPH model is validated by comparing the simulation results to experimental data of triaxial tests on sand under drained and undrained conditions presented in [10]. The drained model is modified to minimize the difference between the experimental and numerical results. Then this model is used to predict the undrained response.

The actual sand sample consists of well-rounded particles. In the numerical model, each sand particle is simulated by clumping two spherical particles with an 80% overlap ratio. The gradation of the particles in the numerical and experimental specimens is alike.

In a DEM model to have a reasonable run-time, the number of particles should be small enough. Therefore, the numerical model dimensions are reduced to 10% of the experimental sample.

The selected friction coefficient and the stiffness are comparable with experimental values reported for quartz grains in [11] and the initial void ratio and the confining pressure have values similar to the actual triaxial tests in [10].

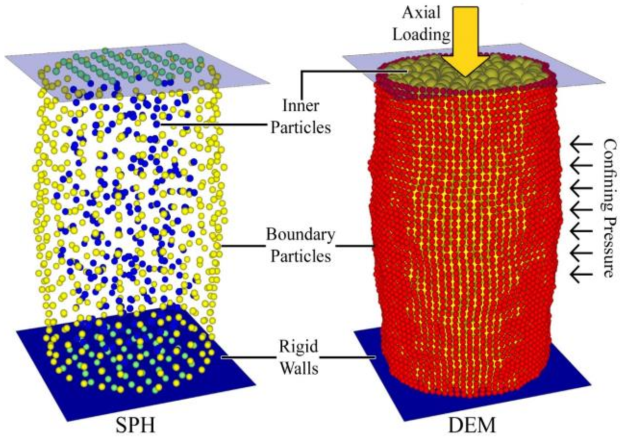

Fig. 1. The DEM particles and the SPH integration points

5- Conclusions

In this study, a novel coupled DEM-SPH model was developed in 3D to simulate the mechanical behavior of saturated granular media without need for a spatial mesh. The particles were modeled using DEM and the fluid was simulated using SPH. Non-spherical particles were generated by bonding two overlapping spheres. The fluid flow and the particle-fluid interactions were included in the model. The model prepared a more accurate understanding of the fluid phase including the pressure distribution in the saturated granular material. The flexible membrane of the triaxial specimen was modeled to apply the confining pressure and the ghost particle approach is used to define the boundary conditions of the fluid.

Immediately after starting axial loading, a pressure wave appeared adjacent to the top wall. This pressure wave formed a transient phase of pore fluid pressure distribution. After finishing the transient phase, a stable phase of the fluid pressure distribution started. During this phase, the pressure gradient throughout the specimen changed gradually. The stable phase finishing time was visually recognized using the pressure distribution contours. This phase lasted up to a threshold axial strain. There was an instable phase of the fluid pressure distribution at axial strains larger than the threshold. The pressure gradient in this phase was significantly affected by the particle sliding and changed randomly in subsequent time steps.

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