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Coupling of soil deformation and pore fluid flow using material point method

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ABSTRACT

This paper presents the formulation and implementation of a numerical procedure based on material point method (MPM) to solve fully coupled dynamic problems that undergo large deformations in saturated soils. The key aspect of this formulation is that it considers two sets of Lagrangian material points to represent soil skeleton and pore water layers. The accuracy of the method is tested by comparing the results to some analytical solutions of consolidation theory. The developed method has been applied to model progressive failure of river levees to illustrate the practical applications. The numerical results show the robustness of the proposed method with regard to large deformations that undergo rapid failure mechanisms.

1. Introduction

Large deformation problems in fluid-saturated granular medium are of great interest in areas such as geophysics, engineering applications and industrial processes. In particular, geophysical and gravity driven flows such as fast catastrophic landslides, flowslides, avalanches, and debris flows cause much damages in many parts of the world due to large travel distances. Similarly failures of man-made structures (i.e. levees, dikes, and embankments) that occur mainly due to intense rainfall and flooding can also results in severe damages due to seepage flows.

In problems such as landslides and flowslides, it is important to predict the travel distances and to identify the post-failure mechanism. Generally it is difficult to use classical mesh based methods such as the finite element method (FEM) to model the behaviour that involves large deformations due to severe mesh distortion errors. Most of the continuum techniques that have been used to model large deformations in granular soils (for instance rapid landslides with long travel distances) often consider soil as a visco-plastic fluid (i.e. Bingham fluid) and fluid-mechanics based hydrodynamics equations have been used [1]. However, it may be difficult to determine these hydrodynamics parameters from typical geotechnical investigation.

The recent advances in particle methods (or meshfree methods) that can be derived in continuum mechanics framework allow us to model large deformation behaviour using conventional geotechnical constitutive models. Wide range of meshfree methods are available in the literature and these include smoothed particle hydrodynamics (SPH) method [2,3], material point method (MPM) [4], finite point method [5], element free Galerkin method [6], particle in cell method [7]. Many of these meshfree methods have been mainly applied to fluid dynamics problems. Only recently they have been applied to study solid mechanics problems, and SPH and MPM have been popular choices.

SPH method is a fully Lagrangian, particle method, in which a continuum material is divided into a set of particles with constant mass and each particle is assigned a spatial distance called a smoothing length in which the physical properties of each particle is smoothed using a kernel function (i.e. cubic spline kernel function) [8]. Although SPH method is widely used in the research community it has certain disadvantages for geotechnical problems. Many geotechnical problems involve boundary interfaces (soil-structure interaction) and its accuracy near the boundaries is less due to insufficient neighbouring particles and thus resulting in loss of consistency, which is a widely investigated topic in the SPH research community. Furthermore, numerical oscillations of particles occur since SPH does not require the velocity field to be single valued (i.e. allows particle penetration). Different stabilisation

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techniques are being used to minimise this issue (i.e. artificial viscosity criterion, average velocity criterion [9,10]).

This study adopts MPM [4,11], in which Lagrangian point masses, or material points, are moved through an Eulerian background mesh (usually a rectangular mesh). Although there is a mesh, it is only used to solve governing equations and purely chosen for computational convenience. All the properties of the continuum are assigned to the material points and all the information is carried out by these material points while the mesh does not carry permanent information. The major advantage of this method compared to other methods is that application of boundary conditions are straightforward due to the presence of background grid, since the boundary conditions can be directly applied to grid nodes as in the FEM. Also particle penetrations are avoided since the particles move in a single valued velocity field (i.e. particle velocities are interpolated from the nodal velocities). MPM has many similarities to FEM and therefore has the advantage of using advanced features that are well established in the FEM.

The single phase MPM and its extension generalised interpolation material point (GIMP) method [12] has been applied to several geotechnical problems that involve large deformations [13–15]. MPM has also been applied to study problems in saturated soil by several researchers [16–20]. It is common in geotechnical engineering to use multi-phase numerical techniques that couples soil deformation and pore fluid flow so that the entire time dependent process of initial undrained behaviour followed by a consolidating behaviour can be modelled. Since MPM is capable of modelling large deformations, it is only required to propose a coupled formulation to model large deformations.

A fully coupled MPM model still requires further development for refinement. Zhang et al. [19], Jassim et al. [17] and Alonso and Zabala [16] use a single layer of material points to model two phase soil-pore fluid behaviour, whereas Shin [20], Mackenzie-Helnwein et al. [21] and Abe et al. [18] use two layers of material points (one for solid skeleton phase and the other for pore fluid phase).

Zhang et al. [19] proposed a coupling MPM based on the u–p form governing equations of saturated soil. In this study, a simple contact algorithm was developed using Coulomb friction law and the results were compared against FEM results. The authors solved problems with dynamic responses of saturated soil under compact/impact with solid bodies and did not apply it to model large deformations. Alonso and Zabala [16] used MPM to simulate progressive failure of Aznalcollar dam in saturated soil condition. The brittle foundation clay was modelled using strain-softening Mohr–Coulomb elasto-plastic model. In this study, each material point was represented by saturated soil with constant mass (i.e. porosity is constant). Internal forces and pressure increments at nodes were calculated using the shape function gradients evaluated at cell centres to avoid issues due to incompressibility (due to the usage of very low permeability), and this approach would be difficult to use with large deformations since it will lead to zero energy modes as observed in FEM with low order elements [22]. Additionally, the Rayleigh damping method was used to reduce numerical oscillations. Similarly, Jassim et al. [17] proposed a coupled dynamic, two-phase MPM formulation via velocity formulation (i.e. consider both solid and fluid phase accelerations) with a single layer of material points and used the method to model the pore pressure development under wave attack on sea dike that does not undergo large deformations. The velocities of both soil and water were stored at single material point and updated using the computed nodal accelerations of soil and water at each step. They used enhanced (averaged) volumetric strains to mitigate spurious pressure fields and locking as observed in FEM, although this method do not guarantee oscillation-free results for saturated soils that undergo incompressibility [23]. Also, the internal force at nodes were calculated using Gauss integration considering the total volume of cells when a cell volume is filled 90% by material points and using averaged stress in cells that is determined by volume averaging of particle stresses (i.e. same stress for Gauss points inside same cell). However, this approach may not conserve energy (i.e. mass conservation is violated due to the use of cell volumes that does not represent true material point volumes).

In reality pore water can move relative to solid skeleton, thus resulting soil material point to have different water velocity than the velocity computed using the above method. When using the inertia terms, the coupled problem is of hyperbolic type and it is necessary consider the motion of the water phase and this can be achieved from considering either the true water velocity field or relative water velocity with respect to the solid skeleton [24]. Shin [20] and Mackenzie-Helnwein et al. [21] modelled solid–fluid mixtures using MPM by representing solid and fluid particles as Lagrangian particles (i.e. two layers of material points). Mixture theory approach was considered in this study and the momentum balance equation for the mixture was solved using Eulerian approach. Solid particles were considered as individual particles (i.e. not considering as a solid skeleton as in soil mechanics) without considering the effective stress concept that is available in soil mechanics. Volume fractions and equilibrium pressures have to be calculated at each time step while using mass balance equation for the mixture for each Eulerian mesh. This formulation faces difficulties since the mixture material would not exactly fill the cell. That is, mass would not properly conserve in these methods due to the calculation method that is used when evaluating volume fraction and pressure of each phase.

Abe et al. [18] were the first to model coupled hydromechanical problems in saturated soil using two layers of material points to represent solid skeleton layer and pore fluid layer based on Biot's mixture theory. In this formulation, the velocity of water material points were evaluated at each time step using the generalised Darcy's law while neglecting the relative acceleration of water with respect to the solid skeleton. This may limit the applicability to extremely rapid motions due to the numerical limitations [25] and also the direct calculation of water velocity in each time step may lead to errors when dealing with large deformations. They have applied this method to simulate the deformation of a river embankment due to seepage failure while using Mohr–Coulomb soil model to represent effective stress behaviour and comparatively good results were achieved with respect to the results from a large scale experiment.

The main object of this study was to develop a MPM methodology that addresses some of the issues described above so that it becomes possible to study large deformation problems in both dry and saturated granular soils. A fully coupled MPM formulation was derived using a mixture theory based approach (i.e. considering the recent versions of Theory of Porous Media that use the Lagrangian description for the solid skeleton and where the theory is based on the concept of superimposed continua with internal interactions and individual states of motion [26]) and then adapting the MPM formulation proposed by [11]. The key aspect of this formulation is that it considers two sets of Lagrangian material points to represent soil and water. Use of Lagrangian particles conserves mass and allows history dependent material models to be used. Also, the discrete equations for the momentum balances are obtained on the background grid similar to the finite element method with an updated Lagrangian formulation. The proposed coupled MPM formulation was implemented into a numerical code and the performance was validated by comparing the results to some analytical solutions of consolidation theory. It was also used to simulate progressive failure of a river levees to illustrate a practical application of the code.