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Studying hydraulic failure in excavations using two-phase material point method

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Abstract

The head difference between the inside and outside of an excavation leads to seepage flow into the excavation. High seepage velocities lead to high seepage pressures that decrease the effective stresses. In extreme cases, the soil fluidizes and cannot sustain the seepage forces, which causes the soil-water mixture to flow into the excavation site.
The problem of hydraulic failure is simulated using the Material Point Method (MPM). The ability of MPM to simulate this phenomenon is shown and some concluding remarks are presented.

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Keywords: material point method; soil-water interaction; excavations; seepage forces; failure.

1. Introduction

It is not uncommon during construction to encounter situations in which the bottom of an excavation is well below the groundwater table. This often requires lowering the water level that results in a decrease of the head of water inside the excavation. The head difference between the inside and outside of the excavation leads to seepage into the excavation. The retaining structures for the excavation, such as e.g. a cofferdam, together with a dewatering system are responsible to control the resulting seepage forces. Due to unknowns in site conditions, or flawed construction, unexpected increases in the pore pressure can develop that further decrease the effective stresses at the

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base of the excavation, which in turn may result in a fluidized soil. This phenomenon is less critical in soil types with high values of hydraulic conductivity like gravel, but in soil types with smaller values for hydraulic conductivity like well graded sand becomes important. The fluidized soil cannot withstand any load and the soil-water mixture may flow into the excavation site, which can lead to a complete failure of the retaining system. Numerical modelling of such cases may help to understand the phenomenon and to avoid such catastrophic incidents.

Numerical modelling of hydraulic failure is a complex task, in which the water-soil interaction, including the possibility of fluidization and sedimentation of the soil particles, must be taken into account. The initiation of the failure can be simulated using the standard finite element method (FEM) (cf. [1] & [2]), but to study the post failure behaviour, advanced numerical models that are capable of simulating large deformations of saturated soil are required.

In this study, the Material Point Method (MPM) is adopted to simulate hydraulic failure in excavations. MPM is a numerical procedure that accommodates large deformations and avoids the mesh distortion problem that is common with the classical FEM method. The effectiveness of this method in soil mechanics for simulating large deformations has been addressed by different researchers. MPM has been successfully applied to model fully saturated soil in a variety of examples; see e.g. Al-Kafaji [3], Bandara [4] as well as Więckowski [5] and Vermeer et al. [6]. Al-Kafaji [3] used the velocity-velocity formulation with single set of material points to represent the soil-water mixture with separated velocity fields for each phase. He studied the wave attack on a sea dike. Bandara [4] used the displacement-displacement formulation with two different sets of material points to represent the soil and water phases separately. She studied the levee failure due to water seepage. Więckowski [5] investigated the erosion of a slope attacked by water. He also used two sets of particles and considered the effect of porosity change in his formulation and used a criterion to define the fluidization of solid particles. Vermeer et al. [6] used the same formulation and studied the collapse of a submerged soil column considering the fluidization and sedimentation of the soil particles.

Other numerical methods are also adopted to investigate the hydraulic heave in excavations, e.g. Grabe and Stefanova [7] used the Smooth Particle Hydrodynamics (SPH) method in their study. This phenomenon is also investigated experimentally by different researchers e.g. Alsaydalani and Clayton [8] and Zoueshtiagh and Merlen [9].

The objective of this paper is to address two necessary aspects required for numerically modelling hydraulic failure in excavations, namely the ability to represent large deformations and to formulate two-phase interactions (including free water, saturated soil, fluidization and sedimentation). The structure of this paper is as follows: Section 2 introduces the two-phase formulation used to describe the fully saturated soil in MPM, which is followed by a simple validation example of a one-dimensional consolidation problem. In Section 3, the Lagrangian formulation for free water is introduced and validated by solving the Poiseulle flow problem, for which an analytical solution exists. In Section 4, the problem of hydraulic failure is simulated and Section 5 provides some concluding remarks.

2. Two-phase formulation of fully saturated soil in MPM

Based on Zienkiewicz and Shiomi [10], the *u-U* formulation, in which displacement of solid (*u*) and displacement of water (*U*) are the primary variables, is chosen to describe the behavior of fully saturated soil. This is due to the fact that, in the *u-U* formulation mapping the pressure as an intensive thermodynamic property between the particles which carry all the state variables and nodes of the background mesh is excluded [3]. Two material point sets are used to represent the solid and fluid phases separately. This is done in order to enable the implementation of free water in the developed program. The starting point is the momentum balance equations of the fluid (1) and fluid-solid mixture (2), from which the displacement (velocity) field of the fluid and solid phases can be calculated, respectively:

$$n\rho_w \frac{d\hat{w}_j}{dt} = n\frac{\partial p}{\partial x_j} + n\rho_w g_j - \frac{n^2\rho_w g}{k}\left(\hat{w}_j - \hat{v}_j\right) \tag{1}$$