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Modelling internal erosion with the material point method

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Abstract

Internal erosion is a general term referring to the mechanism of detachment and movement of soil grains due to water flow through a porous media. It includes many different processes such as piping, soil contact erosion, or suffusion. The study and prediction of these complex phenomena is a recurrent topic in many different fields such as geotechnics, hydraulic and hydrocarbon engineering. This is because internal erosion is one of the main causes of failure of water retaining structures such as dikes and dams. This process also controls the amount of sand production in oil-producing wells. In many cases, such instabilities are related to large deformation of the material involved. The goal of this study is to present a first approach using the Material Point Method to model internal erosion process that occurs in bimodal internally unstable soils. These type of soils consist of a mixture of coarse and fine grains, in which the coarse fraction forms the stable skeleton of the soil, whilst fine grains can be eroded and are able to move freely as a result of seepage flow. The results of a simple numerical test consisting of a soil column subjected to a vertical flow of water are presented. It can be seen that fine fraction is eroded from the solid skeleton depending on the erosion law, and it transported as fluidised material through the saturated porous media.

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1. Introduction

Internal erosion phenomena occur when soil grains are detached from the solid skeleton by seepage flow and transported away from the soil matrix. The study of this mechanism is a significant research topic in geotechnical and hydraulic engineering fields [1,2] since it is the major cause of failure of dams, dikes, and flood embankments.

Two different modes of internal erosion can be distinguished among others: ”internal instability” and ”piping”. Internal instability (or suffosion) is a not localised phenomenon whereby fine particles are transported through the voids of the solid matrix during seepage flow [3]. This may lead to a final collapse of the washed-out soil structure. The term ”suffusion” is also used by many authors to describe the particular case when the internal instability process is non-destructive. Numerous experimental techniques have been developed in order to reproduce erosion phenomena in internally unstable soils [4–7]. On the other hand, the term ”piping” involves the progressive erosion and trans-

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portation of soil grains along a flow path forming a continuous channel of high permeability that, in some cases, can connect upstream and downstream sides of the water retaining structure leading to a general failure. A review on soil piping is summarised in [8] and several laboratory works are presented in [9,10]. According to these definitions, it is important to note that different erosion modes can be closely related. Suffusion occurring within a foundation of a dam can be the triggering factor of piping, which in turn may result in failure of the structure.

The study of internal erosion also appears in oil-producing wells and is a current research field in hydrocarbon and petroleum engineering [11,16]. The prediction of sand production is essential to avoid near-wellbore instabilities and damage of reservoir structures. Several experimental works have been carried out in order to study the erosion processes that appear in the wellbore. These erosion mechanisms lead to local damage and degradation of the soil, which in turn increases the amount of grains that can leave the solid matrix. A review of sand production prediction models was presented by Rahmati et al. [12].

As a result of internal erosion phenomena the material involved in such instabilities experiences large deformations. Eventually, it may lead to the destruction of the structure putting at risk other infrastructure and human lives. The hazard induced by this phenomenon is considered in recent guidelines for practising engineers [13,14]. Therefore, in order to study and predict internal erosion problems and its effects, potential numerical tools must be capable of modelling large deformations and large displacements, apart from being able to simulate the interaction between water, soil skeleton and eroded grains. Traditionally, the internal erosion problem has been implemented in classical numerical methods in the framework of continuum mechanics, such as finite element method and finite differences [11,15–18], but with such techniques large deformation problems are difficult to simulate due to excessive mesh distortion. In order to overcome this limitation, particle-based methods are being developed such as the Discrete Element Method (DEM) and the Material Point Method (MPM). Several authors have been used DEM coupled with computational fluid dynamic models to simulate in a discrete framework the micro-mechanical behaviour of solid particles subjected to internal erosion processes [19–21].

The goal of this study is to present a first MPM continuum approach capable of modelling internal erosion phenomena that occur in internally unstable soils. This mechanism is understood as a mass exchange between solid and liquid phases within a coupled 2-phase flow framework. The current MPM formulation of the Anura3D software [36] is extended and the numerical results of the internal erosion process due to one-dimensional seepage flow are presented.

2. Internally unstable soils

Internally unstable soils are described as those in which a fraction of soil (typically fines) can migrate within the pores of a solid matrix, and is washed out when the soil is subjected to a certain hydraulic gradient. Numerous experimental investigations show that bimodal (gap-graded) soils have been performed; most of them study the behaviour of sand-gravel soils [7,22,23], but others include silt and clay in the mixtures [6,23]. According to Skempton and Brogan [7], in internally unstable soils total stress is mainly carried by the solid skeleton formed essentially by the coarse grains, meanwhile finer fraction remain under lower pressure and can move easily. This fact makes internally unstable soils potentially dangerous since migration of fine fraction can occur at hydraulic gradients much lower than critical gradient given by classical Terzaghi's theory [7].

Several empirical methods have been presented over the last 50 years in order to asses internal stability of soils, and to evaluate if a soil is susceptible to internal erosion [22–26]. These criteria are based on the gradation curve of the soil, and according to Hunter [27], Sherard and Kenney's criteria [22,24,25] are the most robust.

A scheme of the non-destructive process of internal erosion (suffusion) is shown in Figure 1. The sample is represented by means a saturated bimodal soil. As internal erosion progresses fine particles detach from stable solid skeleton are washed-out from the sample while porosity increases. Fine grains transported by the water flow are denominated fluidised grains (Fig1b).

3. Continuum theories of internal erosion

In the past, several models have been proposed in the framework of continuum theory. Vardoulakis et al. [11] formulated a first mathematical approach to model sand production without the influence of the stress field in radial