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Investigation of slope instability induced by seepage and erosion by a particle method

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ABSTRACT

A novel particle based Bluff Morphology Model (BMM) developed by the authors is extended in this paper to investigate the effect of two dimensional seepage on the stability and collapse of soil slopes and levees. To incorporate the seepage in the model, Darcy's law is applied to the interactions among neighbouring soil particles and ghost particles are introduced along the enclosed soil boundary so that no fluid crosses the boundary. The contribution of partially saturated soils and matric suction, as well as the change in hydraulic conductivity due to seepage, are predicted well by the present model. The predicted time evolution of slope stability and seepage induced collapse are in reasonable agreement with the experimental results for homogeneous non-cohesive sand and multiple layered cohesive soils. Rapid drawdown over a sand soil is also investigated, and the location and time of the levee collapse occurrence are well captured. A toe erosion model is incorporated in the BMM model, and the location and quantity of erosion from lateral seepage flow is well predicted. The interplay of erosion, seepage and slope instability is examined.

1. Introduction

Water plays a significant role in the ability of a soil to maintain its shape under a variety of loadings and conditions. Seepage in particular, is often poorly represented in numerical models, therefore, its erosive power is neglected entirely. The structural integrity of levees, rear sides of breakwaters and riverbanks is critical for the protection of life and other assets. Riverbank erosion alone has been recognised as a problem of global significance [1]. It is therefore crucial to establish an accurate model prediction of soil slope stability under seepage conditions.

The stability of river banks, levees and other such soil slopes has received much attention in the past. Since Slope/W [2], General Limit Equilibrium and Finite Element Methods of modelling slope stability have been used widely as engineering design tools to predict the safety of these slopes. The majority of these models compute the Factor of Safety (FoS) of a soil slope based on the limit equilibrium of rotational or translational failures of the soil body, by dividing the mobilised slope up into slices or wedges [3–5].

Another alternative to experimental observations of FoS is an equilibrium model such as the Discrete Element Method (DEM). This method uses a mass-spring contact between soil particles and considers the movement of soils at a particulate level. This interparticle force is the key driver behind the entire model output, and is not based on traditional soil strength values, but rather back-analysed functions [6]. This method is adapted by many commercial codes, for example Particle Flow Code (PFC) which can be used to model the movement of a slope. The particle nature of this model makes it highly adaptable to scenarios of high strain, however the mechanics of the model make it difficult to produce detailed Factor of Safety predictions.

The slope stability problem is further complicated by the presence of seepage, erosion and undercutting caused by surface water. A partner program to Slope/W, SEEP/W developed by Krahn [7], incorporates the movement in the water table, as well as dynamic pore water pressures, in the analysis of slope stability. This and other slope stability models use computational meshes fixed in space. The model becomes unstable and inaccurate when high strain caused by large relative movement, or significant erosion, is present. Two dimensional seepage often generates erosion and undercutting through surfacing water. This has been investigated by Chu-Agor et al. [8,9] where a null region without soil strength is artificially created to emulate the effect of removed soil properties.

The effect of seepage is important to identify for a number of reasons. Seepage may reduce the effective stress of surface soil particles to zero (liquefaction), leading to erosion and episodic collapse of the bank [10]. The seepage can negatively affect the bank stability either through reducing the restraining forces on a potential slip surface, or by increasing the mobilising forces above

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it. Reducing the restraining forces on the soil slope can occur through the combination of toe erosion or a loss of soil suction. Increasing the mobilising forces on the slope can occur through an increase in soil weight or an increase in pore water pressures. In some cases, falling external water tables cause a loss of containing pressure when the water level recedes [11].

Negative pore water pressure, known as matric suction, causes an apparent cohesion that significantly increases the slope stability. The loss of this matric suction when the soil within a bank is saturated, significantly reduces bank stability, and thus may trigger bank failures or episodic collapse [12].

Inundation of the soil by rainwater or lateral seepage has been identified as an important factor in the stabilities of banks, slopes [13], bluffs, breakwaters [14] and levees. The particle based Bluff Morphology Model used in this paper was originally developed to analyse the stability and collapse of static slopes and coastal bluffs by Vandamme et al. [15].

Using a particle method to solve quasi-static problems allows an easy discretisation of the soil domain and offers a rapid seepage and stability analysis due to the logical arrangement of particles. It is also straight forward to construct complex geometric domains and resolve multiple soils within the domain using the particle method. Furthermore, it offers a simple export to the WCSPH failure model.

Hexagonal tessellation is used as it is the most spherical particle shape that still tessellates. It therefore allows for the best approximation of truly 2D movement of the fluid and for the failure plane analysis to operate with minimised complication. Once failure has been shown to occur, the failure mechanics require the adoption of a spherical (or near spherical) particle to avoid complications with angular particle interactions and their associated complexities.

In this paper, we will extend this particle method for slope stability by incorporating the key soil parameters related to seepage and erosion described above and multiple soil types. The model results are compared to the laboratory experiments and the outputs of the Slope/W model. The aim of this paper is to investigate the change in slope stability, and the mechanisms and times of collapse induced by two dimensional seepage.

2. Extension of particle based Bluff Morphology Model

The particle based Bluff Morphology Model [15] combines a multiple wedge displacement method with an adapted Weakly Compressible Smoothed Particle Hydrodynamics (WCSPH) method. At first, the wedge method is applied to compute the stability of the bluff. Once the critical failure mechanism of the bluff slope has been identified, and if the Factor of Safety for the mechanism is less than 1, the adapted WCSPH method is used to predict the failure movement and residual shape of the slope. This model is extended to incorporate the seepage, erosion and undercutting in this section.

2.1. Stability evaluation

The model set-up uses a hexagonal particle tessellation when considering a static earth profile. Hexagonal tessellation is used as tessellation is required for the best approximation of two dimensional fluid movement, and minimises complication of the failure plane analysis. Once failure has been shown to occur, the failure mechanics require the adoption of a spherical (or near spherical) particle to avoid complications with angular particle interactions and their associated complexities, hence, hexagonal particles are well suited to this model. These particles are arranged in order to best represent the soil profile, and then assigned a set of scalar parameters including mass, pore water pressure, position, and earth material properties. It would be theoretically possible to assign an individual set of earth material strength properties to each particle within the model, although this would significantly slow the analysis down. Different from [15], multiple soil types are considered with each particle representing one of the soil types in this paper. Each soil type is taken as homogenous within its boundaries, and there is no variation in the individual soil properties within its boundary.

In order to assess the stability of a soil slope, the model uses a displacement-stepping wedge method based on the concept of McCombie [5], and detailed in [15]. This allows for a variety of potential slip surfaces to be analysed, in particular, from large rotational failures to linear translational failures. The conceptualised cycle mechanism to find the failure surfaces is shown in Fig. 1. Initially, the method assumes an entry point of an arbitrary failure surface on the soil surface, and then an exit point above this. Many potential slips that fit these two points are then analysed, from linear to a near-circular analysis where the back of the potential failure surface is vertical (steps 3 and 4 in Fig. 1). If the slip surface daylights (point A), then the entry point is moved to the appropriate place. The exit point is then stepped across the domain repeating this loop, and then the entry point is moved and the loop begins again.

Once the analysis of each slope is completed, the Factor of Safety along the slope boundary is computed. This in turn can be assigned to the particles on the boundary of the slope, and each particle retains the lowest Factor of Safety assigned to it over many potential slip surfaces. This procedure provides the spatial distribution of Factor of Safety of the entire slope at any given time.

Each soil used in the model is defined by the soil strength parameters of cohesion c' and internal angle of friction (φ'), as well as the effective stress (σ'), unit weight, permeability and porosity. This is loosely based on the Smoothed Particle Hydrodynamics (SPH) model which offers a computational time saving and reduces memory demand, each model particle is taken to represent an area of single soil using the Mohr–Coluomb shear profile. The values of these parameters are taken from the average laboratory experiments of the given soil. The shear strength τ may be calculated using the following formula, if the soil is fully saturated, or completely dry:

$$\tau = c' + \sigma' \cdot \tan(\phi') \quad (1)$$

The slope stability model uses a displacement stepping algorithm, where the mobilised cohesion and the angle of internal friction are increased incrementally and proportionally with the strain along the boundary of the mobilising soil until the shear strength matches the mobilising force. The strain itself is only computationally significant if soils mobilize at different rates, or if the output of the strain is extrapolated as a failure model. The ratio of maximum shear strength to the shear strength required for stability is defined as the Factor of Safety.

Where multiple soil types exist in the same wedge boundary, the model calculates the shear strength pro-rata to the proportion of soil types. These soil types do not have to reach peak strength at the same time for the computation to work. Due to the numerical averaging of the soil types, increasing the number of wedges in each potential slip surface allows for greater accuracy of the shear strength, however it also increases the computational time required. In this paper, analyses were performed using 6–12 wedges per slip which was found to be sufficient for the present study.

The minimum Factor of Safety of each particle along the base of a potential failure surface is stored, and after all potential failure surfaces have been analysed, the model produces a cross-sectional diagram of the Factors of Safety, showing a stability map of the slope.