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Research Paper

Particle mechanics modeling of creep behavior of rockfill materials under dry and wet conditions

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ABSTRACT

Rockfill is an important construction material for infrastructure engineering, such as dams, railways and airport foundations, which display a long-term post-construction settlement. However, the main mechanisms for rockfill creep and weathering influence still remain poorly understood. Particle mechanics method is used to understand the rockfill creep process under dry and wet conditions. Different bond-aging models and wetting models that represent different degradation and weakening mechanisms are compared, in order to clarify the principle and secondary mechanisms for rockfill creep and weathering influence. The results show that rockfill aggregate breakage in terms of angularity abrasion is the main source for rockfill creep under dry state. Wetting can induce additional strain mainly due to the reduction of contact friction coefficient, i.e. lubrication, and the bond strength reduction just plays a secondary role in producing additional strain. The earlier the wetting occurs during rockfill creep, the more rapidly the rockfill becomes stable. The wetting–drying cycles can induce strain evolution in a 'stepped' way, which is in agreement with experimental observation. The practical implications from the modeling and the outstanding issues in this study are also discussed.

1. Introduction

Rockfill materials, which are coarse and mainly composed of quarry rock debris or crushed rock fragments, have been widely used in many infrastructure projects, such as dams, railways and airport foundations in mountain area. It is observed that creep settlement at these infrastructures continues for a long period after their construction [52,43]. The operability and safety of railways and airports impose tight limits for post-construction settlements of the supporting embankments. Significant post-construction settlements may affect the infrastructure's serviceability, or even induce engineering disaster. In addition to time-dependent strains under constant external loading, significant rockfill settlement can also be caused by other environmental factors, such as rainfall or flooding. There is therefore a pressing need to clearly understand the physical and chemical mechanisms responsible for rockfill creep under dry and wet conditions, in order to derive more comprehensive constitutive models, interpret safety monitoring records without misleading conclusions, make more reliable predictions of creep settlement and minimize maintenance costs during the infrastructure's working life.

Over the years, many laboratory or in-situ experiments have been conducted to study the complex settlement behavior of rockfill-type materials (Takei et al. [53]; McDowell and Khan [40]; Lim [26]; Ionescu [18]; Oldecop and Alonso [45]; Huang et al. [13]; Cao [3]; among others). The results showed that rockfill creep, during which crushing continuously occurs, is mainly affected by stress level, initial density, particle characteristics, saturation and other environmental factors such as temperature and freeze and thaw actions. Based on these experimental results, a number of constitutive models have been proposed to account for rockfill creep, in terms of a logarithmic relationship between time and long-term strain (e.g. [52,41,21]. However, due to the fact that physical tests are not able to monitor the microscopic rockfill response at an individual aggregate level, the nature of creep and the underlying mechanism of degradation have not been fully understood. In this way, most of the constitutive models are purely empirical and lacking in theoretical support, and therefore cannot reflect the nature of the observed time-dependent rockfill settlement.

The particle mechanics method, as an alternative to laboratory or in-situ experiments, has been used by many researchers to explore the micro-mechanism of granular materials. There are mainly three approaches to represent rockfill aggregates in particle mechanics models: (1) the rockfill blocks are directly modeled using rigid circular or polygonal-shaped particles [55,42,30,29,50,56,14], but note

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that the circular elements cannot consider the angularity of rockfill blocks compared with polygonal elements; (2) using a 'clump', which is a single entity of overlapping particles and is rigid internally and deformable at the external boundary, rockfill blocks of irregular shapes can be modeled [6,31–34,17]; (3) one treats rockfill blocks as clusters of bonded circular particles, which can reflect the angularity of rockfill blocks to some extent [20,39,4,27,54,51,23,24].

It is known that crushing (i.e., grain fracture process) in a granular material subjected to compression is one of the main causes for rockfill settlement. Particle mechanics method has also been attempted to model rockfill block breakage. The basic elements in particle mechanics models cannot break, but an alternative of replacing the original particles that fulfill failure criterion with a set of smaller particles was proposed to simulate particle breakage [55,30,29]. However, this replacement cannot conserve mass balance. Clumps are also unbreakable, and this disadvantage restrains their use in accurate modeling of mechanical behavior of rockfill materials. The cluster of bonded circular particles can be regarded as an cohesive granular aggregate, where micro-cracks can initiate and propagate depending on the bond strengths and contact forces and eventually the macro-cracks form [20,4,54,51,57].

Generally, the above studies have demonstrated that particle mechanics method is able to and also a robust tool to simulate the rockfill mechanical behavior. However, those studies mainly focused on the rockfill behavior subjected to static and dynamic loading, with rare consideration of rockfill creep and other weathering factors like saturation or wetting–drying cycles. Kwok and Bolton [23,24] studied soil (e.g., sand or clay) creep using particle mechanics method, considering time-dependent contact friction coefficient and bond strength. Tran et al. [54] and Silvani et al. [51] incorporated bonding deterioration models into particles mechanics method, in order to simulate the rockfill creep, but they did not consider the time-dependent contact friction coefficient.

In addition, other numerical methods like the finite element method incorporated with continuum damage mechanics [28] and the combined finite-discrete element method [37,36] are also able to simulate particle breakage, but they have not been widely used to simulate rockfill mechanical behavior.

Overall, the main objective of this study is to further advance the understanding of the micro-mechanisms of rockfill creep using particle mechanics method, and the main novelty is to systematically study the effects of wetting and wetting–drying cycles on rockfill settlement.

2. Methodology

2.1. Mechanism of rockfill creep

Creep settlement of rockfill ground is mainly due to delayed grain fracture process [51], and particle breakage mainly occur in the forms of abrasion and total fragmentation. Grain fracture process is a rate-dependent process that can start at a relatively low stress, and results in gradual changes in rockfill fabric and packing, which is mainly governed by grain size and shape, the magnitudes of the applied stresses, and the mineralogy and strengths of individual grains.

For a brittle rock that is compressively loaded, two strengths can be defined: (1) when the applied stress reaches the '*short-term strength*' of the rock block, failure occurs immediately; (2) otherwise, failure progressively occurs when the applied stress reaches a value defined as the '*long-term strength*'. The ratio of long-term strength over short-term strength is always less than 1. In addition, a threshold for the stress is defined above which strength degradation initiates [25,49]. This strength degradation process can be understood as a process of crack growth due to stress corrosion, from a microscopic perspective. A terminology of 'subcritical crack growth' can be used, and crack growth velocity is zero for stress-intensity factor less than its limit values. Serial laboratory tests carried out on different rocks showed that wreathing processes, such as water, temperature, freeze and thaw actions, can accelerate the crack propagation velocity and then reduce the rock's strength and failure time. The influence of these actions is different for each material and also depends on the state of the rock studied (rock alteration, degree of saturation, temperature) [1,44].

2.2. Effects of water on rockfill creep

It was observed that an accelerated rate of compression was induced by wetting the rockfill specimens [22,46]. Water acts as lubricant at the interparticle contact points, and results in lower friction coefficient [12]. On the other hand, water can cause the initial crushing strength of a single particle to reduce and strength variability to increase, due to the following two weakening mechanisms: (1) physically the pressurized pore water can weaken and embrittle rocks; (2) chemically the pore water can lower the fracture energy [2]. In other words, by wetting rockfill materials, mechanical parameters such as short term strength, long term strength, threshold of strength degradation and contact friction coefficient may suddenly decrease. Many experiments have found that the stress–strain behavior of rockfill initially follows the dry state curve, and is transformed to follow the wet state curve when subjected to saturation at elevated stress level [11,38,9,10,18].

2.3. Modeling rockfill creep using particle mechanics method

The bond force vector (F_b) can be resolved into normal (F_n) and shear (F_s) components with respect to the contact plane (Fig. 1a), and thus the stress state (σ) in a parallel bond can be expressed as,

$$\sigma = \sigma_n \vec{n} + \tau \vec{s} \tag{1}$$

where σ_n and τ represent the normal and shear stresses, respectively; $\vec{n}$ and $\vec{s}$ are the unit vectors that define the contact plane. If the tensile stress exceeds the tensile strength ($\sigma_n \geqslant \sigma_{bc}$) or the shear stress exceeds the shear strength ($\tau \geqslant \tau_{bc}$), then the parallel bond breaks, and it is removed from the model along with its accompanying force, moment and stiffness. A few bond-ageing models, in terms of reducing parallel bond strengths or diameter (Fig. 1b), have been developed in particle mechanics method [48,54,51], some of which have been used to model rockfill creep. Below these bond-ageing models are briefly reviewed and compared.

2.3.1. Bond-ageing model in Tran et al. [54]

Tran et al. [54] proposed a bond-ageing law for the evolution of bond strength in the following form,

$$\sigma_b^t = \begin{cases} \sigma_b^0 & \beta_1 \sigma_b^0 > \sigma_n \\ \sigma_b^0 \left[1 - \beta_3 \int_{t_0}^{t} \exp\left(\beta_2 \frac{\sigma_n}{\sigma_b^0} - \beta_1 \right) dt \right] & \sigma_b^0 \geq \sigma_n \geq \beta_1 \sigma_b^0 \\ 0 & \sigma_n > \sigma_b^0 \end{cases} \tag{2a}$$

$$\tau_b^t = \begin{cases} \sigma_b^0 & \beta_1 \sigma_b^0 > \sigma_n \\ \tau_b^0 \left[1 - \beta_3 \int_{t_0}^{t} \exp\left(\beta_2 \frac{\sigma_n}{\sigma_b^0} - \beta_1 \right) dt \right] & \sigma_b^0 \geq \sigma_n \geq \beta_1 \sigma_b^0 \\ 0 & \sigma_n > \sigma_b^0 \end{cases} \tag{2b}$$

where σ_b^0 and σ_b^t are the short- and long-term normal strength, respectively; τ_b^0 and τ_b^t are the short- and long-term shear strength, respectively; β_1, β_2 and β_3 are three empirical parameters, which depend on aggregate's size and shape and the material properties.