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

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A B S T R A C T
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-aggregating 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...
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 [20,39,4,27,54,23,24].

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 particle 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 weathering 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 ($\sigma$) in a parallel bond can be expressed as,

$$\sigma = \sigma_n n + \sigma_s s$$

where $\sigma_n$ and $\tau$ represent the normal and shear stresses, respectively; $n$ and $s$ are the unit vectors that define the contact plane. If the tensile stress exceeds the tensile strength ($\sigma_n > \sigma_{nt}$) or the shear stress exceeds the shear strength ($\tau \geq \tau_{tc}$), 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,

\[ \sigma_b^0 = \begin{cases} \sigma_n^0 & \sigma_n^0 \geq \sigma_n > \beta_1 \sigma_0^0 \\ \beta_1 \sigma_0^0 > \sigma_n \end{cases} \]

\[ \tau_b^0 = \begin{cases} \tau_n^0 & \tau_n^0 \geq \tau_n > \beta_1 \tau_0^0 \\ \beta_1 \tau_0^0 > \tau_n \end{cases} \]

where $\sigma_{nt}$ and $\tau_{tc}$ are the short- and long-term normal strength, respectively; $\tau_{nt}$ and $\tau_{tc}$ are the short- and long-term shear strength, respectively; $\beta_1$, $\beta_2$ and $\beta_3$ are three empirical parameters, which depend on aggregate’s size and shape and the material properties.
defines stress threshold for strength degradation
are two rate

\[ g_u = \frac{D_0}{m} \left( \ln \left( \frac{F_s}{\mu + F_n} \right) - 1 \right) \left( 1 - mD_0 \right) \]

where \( \eta \) is a characteristic time; the term \( \frac{1}{m} \left( 1 - \frac{F_s}{\mu + F_n} \right) \) is a value of ultimate damage, denoted as \( D_0 \), and is determined according to \( g_u = 0 \). Note that \( D \) may jump from its ultimate value \( D_0 \) to its maximum value \( 1/m \). For a bond under a condition of \( g_u \geq 0 \) and \( g_u < 0 \), bond breakage occurs in finite time, which is determined as follow,

\[ t_f = \frac{\eta}{m} \ln \left( 1 + \left( \frac{F_s}{\mu + F_n} \right) - 1 \right) + \frac{\eta}{m} \ln \left( \frac{C_0}{C_u} \right) \]

2.3.3. Diameter-ageing model in Potyondy [48]
Based on stress corrosion theory, a corrosion rate law for the bond diameter, \( d' \), was proposed by Potyondy [48],

\[ d' = \left\{ \begin{array}{ll} d^0 & \sigma_n > \sigma_a \\ \left( d^0 - \frac{d^0 - d}{\sigma_n^{\prime}} \right) \exp \left( \frac{\sigma_n^{\prime} - \sigma_n}{\sigma_b^{\prime}} \right) & \sigma_b^{\prime} \geq \sigma_n \geq \sigma_a \\ 0 & \sigma_n > \sigma_b^{\prime} \end{array} \right. \]

where \( d^0 \) is the initial parallel bond diameter; \( \sigma_n \) is the normal stress acting on the parallel bond; \( \sigma_a \) is a threshold stress, below which the stress corrosion reaction ceases; \( \sigma_1 \) and \( \sigma_2 \) are two rate constants. As damage proceeds, the effective bond stiffness decreases, which allows a macroscopic load redistribution to occur throughout the material. The elapsed time to bond failure can be determined by,

\[ t_f = \frac{d^0 - d}{\sigma_1} \exp \left( -\frac{\sigma_n^{\prime}}{\sigma_a} \right) \]

2.3.4. Comparison
For the above three damage-rate laws, the elapsed times to bond failure under normalized normal stresses/forces are compared in Fig. 2. If proper values were given to the empirical parameters in these bond-ageing models, similar elapsed times could be obtained from the three models. This means that any one of them can be used to study the rockfill creep in a generic study, if the empirical parameters could be calibrated with experiments. In this paper, bond-ageing model in Tran et al. [54] was used because of its relatively simple mathematical form and clear physical meaning.

2.4. Modeling water weakening in particle mechanics model
Water weakening can basically be characterized as two mechanisms: reducing fracture energy and friction coefficient, and these two mechanisms are positively correlated, i.e. the operative mechanisms are effective on both crack propagation and frictional sliding [2]. In order to consider effects of wetting on bond degradation and rockfill arrangement, both normal and shear bond strengths and contact friction coefficient are reduced by a specified ratio, \( \lambda_3 \), after an instantaneous and homogeneous wetting. It is assumed that after a wetting–drying cycle, both normal and shear bond strengths and contact friction coefficient partially convert back to their initial values. Compared with the bond-ageing model
accounting for wetting in Tran et al. [54], we consider water weakening by reducing bond strengths instead of three empirical parameters ($b_1$, $b_2$, and $b_3$). Compared with the way of accounting for wetting in Silvani et al. [51], short-term strength, stress threshold for strength degradation and contact friction coefficient decrease simultaneously in this study, instead of only short-term strength or long-term strength.

3. Modeling

3.1. Model setup

Cao [3] conducted large scale compression experiments on rockfill specimens, under dry and wet conditions, respectively. The results showed that wetting can speed up creep, and thus cause a larger creep strain. Wetting–drying cycles can induce creep strain evolve in a pattern of ‘steps’. In this study, rockfill creep under dry and wet conditions was modeled using two-dimensional particle flow code, PFC2D [19], and was compared with experimental observation in Cao [3].

A rockfill aggregate is represented by an two-dimensional dense packing assembly of circular disks of non-uniform sizes, and the disks are bonded in the normal and shear directions at all contacts that possess finite (normal and shear) stiffness and (tensile and shear) strengths [47]. The contact points between rockfill aggregates are assigned zero bond strengths, but a nonzero friction coefficient. In this way, the surface roughness of rockfill aggregates can be naturally simulated by the arrangement of disks, but the irregular shapes of rockfill aggregates cannot be modeled perfectly. More details about the assumptions and laws of particle flow can be found in the literature (e.g., [19, 47]). This section mainly focuses on the model setup and modeling procedure of rockfill creep during one-dimensional confined compression.

According to the basic specimen-genesis procedure in Potyondy and Cundall [47] and Itasca [19], 5000 disks were packed into a square box with a side length of 200 mm to build up rock matrix, through four steps, i.e., compacting initial assembly, establishing specified isotropic stress, removing ‘floating’ particles and installing parallel bonds. The average disk radius was 1.4 mm, with maximum and minimum of 1.8 mm and 1.1 mm, respectively. By projecting a sketch of artificial rockfill specimen including 120 aggregates on the particle mechanics model (Fig. 3a), and removing the disks located in the voids, a numerical rockfill specimen was generated (Fig. 3b). The average radius of rockfill aggregates was about 9.18 mm, with the maximum and minimum of 11.18 and 6.82 mm, respectively. Other micro-parameters are listed in Table 1, the values of which were the same or similar to those in the literature pertaining to rock behavior modeled using PFC [57]. Numerical biaxial tests [19] were carried out, and showed that the micro-parameters can reflect the nature of rockfill materials.

3.2. Modeling of one-dimensional compressional creep

During one-dimensional compression, the normal stresses on the upper wall gradually increased to the required values and then remained constant using the servo control algorithm [19]. Once bond degradation became active, micro-cracking in rockfill aggregates may be induced and macroscopic settlement of rockfill specimen occurred. The development of micro-cracks and breakage of rockfill aggregates, normal displacement of the upper wall and bond force chain in the rockfill specimen were monitored during the creep test.
During the creep test, mechanical and bond degradation calculations were run circularly [48]. During mechanical calculation, bond degradation calculation was hung on, and sufficient time steps are cycled until a quasi-static state was reached. During bond degradation calculation, the state variables like forces and displacements were kept constant, and bond strengths were adjusted based on the bond-aging law and state variables. This approximation is reasonable because mechanical process is relatively shorter compared with bond degradation process. Note that the time step in mechanical calculation is a ‘false’ time, whereas the time step in bond degradation calculation represents the real time. The first false time can be understood as the ‘numerical time’ that is needed for the computer to make the system reach the balanced state. The latter real time is the ‘creep time’ during which the bond strength evolves but there is no evolution of the whole granular structure [54]. Alternatively, the time step in bond degradation calculation can be fixed at a constant value or self-adaptively adjusted. Potyondy [48] proposed a self-adaptive procedure based on the estimated elapsed time ($t_f$),

$$\Delta t_b = t_f / n_c$$  \hspace{1cm} (10)

where $\Delta t_b$ is the time step for bond degradation calculation; $t_f$ can be calculated using Eq. (4) and represents the estimated elapsed time to the next parallel bond failure; $n_c$ is the number of cycles until the next parallel bond breaks.

### 3.3 Modeling of wetting and wetting–drying cycles

Since no models that consider the effects of wetting or wetting–drying cycles on rockfill creep have been widely used, the wetting model in Tran et al. [54] was used and some new models based on the water weakening mechanisms in Baud et al. [2] are explored: (1) Water weakening model I (W1), Tran et al. [54] took into account the wetting effects by decreasing $\beta_2$ and increasing $\beta_3$, i.e., changing the degradation rate; (2) Water weakening model II (W2), only bond strengths decrease by $\lambda_1$ due to the lower specific surface energy in a fluid environment; (3) Water weakening model III (W3), only contact friction coefficient decreases by $\lambda_1$; (4) Water weakening model IV (W4), both contact friction coefficient and bond strengths decrease by $\lambda_1$, which can be regarded as an addition of W2 and W3. The reduction ratio of 4% was chosen according to Baud et al. [2], which showed that the ratio of the values of sandstone mechanical parameters under wetting state over that under dry state is about 0.83–0.97. Through comparing the obtained results by using different models, it is intended to clarify the dominant weakening mechanisms during wetting.

When one dimensional compressional creep started, wetting occurred instantly at a specified time, which was modeled using the above four models, respectively. It was assumed that the rockfill specimen can be wetted in a sufficiently short time that was neglected in this study. For each wetting–drying cycle, firstly the above wetting models were used for wetting, and then the parameters were partially converted back to their original values for modeling drying process. This is supported by the recent experimental studies which showed that rock mechanical properties gradually decreased with the increasing numbers of wetting–drying cycles [7,8].

### 4. Results

#### 4.1 Rockfill creep under one dimensional compression

The creep strain–time curves under different constant normal stresses of 0.94 MPa and 1.14 MPa are presented in Fig. 4, and both primary creep and secondary creep phases were observed. Generally, the higher the normal stress is, the larger are the creep strain rate during primary creep phase and the eventual creep.

#### Table 1

<table>
<thead>
<tr>
<th>Parameter (unit)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of balls (–)</td>
<td>5000</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>2230</td>
</tr>
<tr>
<td>Contact modulus (GPa)</td>
<td>4.0</td>
</tr>
<tr>
<td>Ratio of ball shear to normal stiffness (–)</td>
<td>0.4</td>
</tr>
<tr>
<td>Contact friction coefficient (–)</td>
<td>0.3</td>
</tr>
<tr>
<td>Parallel bond radius multiplier (–)</td>
<td>1.0</td>
</tr>
<tr>
<td>Parallel bond modulus (GPa)</td>
<td>4.0</td>
</tr>
<tr>
<td>Ratio of parallel bond shear to normal stiffness (–)</td>
<td>0.4</td>
</tr>
<tr>
<td>Parallel bond normal strength, mean (MPa)</td>
<td>10.0</td>
</tr>
<tr>
<td>Parallel bond normal strength, standard deviation (MPa)</td>
<td>3.0</td>
</tr>
<tr>
<td>Parallel bond shear strength, mean (MPa)</td>
<td>10.0</td>
</tr>
<tr>
<td>Parallel bond shear strength, standard deviation (MPa)</td>
<td>3.0</td>
</tr>
<tr>
<td>Empirical parameters $\beta_1$, $\beta_2$ and $\beta_3$</td>
<td>0.4, 40 and $5 \times 10^{-11}$</td>
</tr>
</tbody>
</table>

![Fig. 4. Rockfill creep under dry condition.](image-url)
strain. This indicates that normal stress is a critical factor that not only determines the absolute value of creep strain, but also affects the rate of creep strain evolution. Compared with experimental curves, the creep strain curves exhibited a drastic ‘jump’, which is probably due to rockfill aggregate crushing and rearrangement. The curves of creep strain that were obtained by employing fixed or self-adaptive time steps for bond degradation calculation, are also compared in Fig. 4. Even though both approaches can capture the main features of rockfill creep, some differences existed during the primary creep phase. For the modeling in this study, the calculation time by both approaches were similar. In other words, the procedure of self-adaptive time steps did not improve the calculation efficiency significantly. The scheme of fixed time step was used in modeling rockfill creep under wet condition, and thus the wetting and drying time can be accurately controlled.

Using the case under normal stress of 1.14 MPa to explain the microscopic mechanisms responsible for rockfill creep, the axial strain and the number of micro-cracks are plotted in Fig. 5. The similarity between the strain and micro-crack curves indicates that the reduction of parallel-bond strength with time and the formation of micro-cracks are the main mechanism of producing creep [48]. Micro-cracks distribution is presented in Fig. 6, which shows that the micro-cracks formed mainly due to tensile failure. Micro-cracks mainly occurred in those rockfill aggregates which are on the force chains (Fig. 6). Rockfill aggregate breakage occurred in the form of abrasion (angularity/corner breakage), which was also observed in Takei et al. [53]. However, total fragmentation (particle splitting) was not found in this study. Indraratna et al. [15] also showed that most ballast degradation under cyclic loading is primarily the consequence of corner breakage, rather than particle splitting.

4.2. Effects of wetting and wetting–drying cycles on rockfill creep

When a dry rockfill specimen was saturated during one dimensional compression creep, an initial sudden settlement was observed, especially when the wetting model W4 was used (Fig. 7a). Using the wetting model W4 predicted the largest strain, whereas the smallest strain was obtained when the wetting model W1 was used. The similar strains were obtained by employing the wetting models W3 and W4, but the strain increased more rapidly for W4, immediately after wetting. From the above comparison, it may be concluded that the initial sudden settlement is primarily

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**Fig. 5.** The number of micro-crack increase during rockfill creep under normal loading of 1.14 MPa.

**Fig. 6.** Rockfill aggregate breakage during one dimensional compression creep under normal loading of 1.14 MPa. Black and red short lines indicate the tensile and shear micro-cracks, respectively. The angularity (sharp corners) of aggregate leads to stress concentrations and breakage.
induced by the reduced contact friction coefficient, which results
into rockfill sliding and rearrangement. Wetting induced weaken-
ing (bond strength reduction) plays a secondary role in speeding
up the creep rate. Due to wetting, some bond force chains changed
and more micro-cracks at rockfill aggregate angularities were
induced (Fig. 7b–d).

The effect of wetting time when the wetting occurred during
creep was also studied, and the corresponding strain evolution
curves modeled using W4 are compared in Fig. 8. A similar final
creep strain was obtained for different wetting times. During the
primary creep phase, micro-cracking and stress redistribution
occurred in a drastic way, wetting could further accelerate the
micro-cracking propagation speed. Therefore, rockfill specimen
that was wetted earlier can reach the secondary creep phase more
quickly. However, if wetting occurs during the secondary creep
phase, the stable compact state of rockfill was broken again.
Additional time was required for the rockfill specimen to reach
another stable state. Wetting-induced strain is strongly dependent
on the stress state and aggregate structure.

The effects of wetting–drying cycles on rockfill creep were also
modeled using W4, and the creep–strain curves are compared with
the experimental results [3] in Fig. 9. Two wetting–drying cycles
were considered in this study. Similar to the experimental obser-
vation, the numerical results also show that the significant strains
were induced during wetting–drying cycles, and the induced strain
in the second wetting–drying cycle was smaller than that in the
first one. During each wetting–drying cycle, both primary creep
and secondary creep phases were observed. Compared with exper-
imental results [3], the wetting induced strain increased more
rapidly in the numerical modeling. The possible reason is that

![Figure 7: Effects of wetting on rockfill creep using different wetting models.](image-url)
the numerical rockfill specimen was assumed to become wet instantly, but more time was needed to wet the rockfill specimen during experiments.

5. Discussion

5.1. Micro-mechanism for rockfill creep under dry state

Luong [35] summarized that the deformation of granular materials under loading mainly results from three mechanisms: (1) consolidation – the change in volume of particle assemblies; (2) distortion – the change in aggregate shape due to sliding and rolling; and (3) attrition – particle crushing and breakage leading to rearrangement and compaction or dilation. This study shows that aggregate breakage is the main factor contributing to rockfill creep (Fig. 10), whereas both consolidation and distortion play a minor role in rockfill creep. Takei et al. [53] studied the time-dependent deformation of chalk bar specimen, and their results showed angularity/corner breakage was the dominant failure pattern of chalk bars (Fig. 6d), which is the same as the modeling results in Section 4.1. In addition, particle splitting also appeared in a few chalk bars in Takei et al. [53], but it did not occur in this modeling. The possible reason is that regular (cubic or hexagonal) packing in their experiments may induce a pair of relatively larger compression force in one direction than that in other directions. However, numerical rockfill aggregates are not perfectly circular and randomly packed in this paper, and thus the contact forces acting on the single aggregate are in a complicated way. Similarly, both Takei et al. [53] and this study did not find significant aggregate rotation, which also plays a negligible role in rockfill creep.

5.2. Proper wetting models in particle mechanics method

Ciantia et al. [5] classified the bonds into depositional bond, which is consisting of mineral powders and can be totally damaged as water penetrates the rock pores, and diagenetic bond which is formed during diagenesis and may be gradually weathered by water for a long period of time, depending on both the rate of fluid–mineral reactions and the ionic composition of the bulk fluid. These mechanisms have been included in wetting models W1, W2 and W4 through speeding up the weathering rate or reducing bond strengths. In addition, wetting models W3 and W4 considers contact friction coefficient reduction in a fluid environment. The results show that the additional strain induced by bond strength reduction or weathering rate increase is less than that caused by contact friction coefficient reduction (Fig. 7). In Fig. 9, the strain evolution during two wetting–drying cycles modeled by W4 is in agreement with the laboratory experiments in Cao [3]. The
similarity of strain evolution in terms of 'stepped' shape indicates that a reduction in contact friction coefficient and bond strength should be the main weathering mechanism due to wetting. Therefore, it is concluded that sliding/rotation due to the reduced contact friction coefficient and further abrasion due to weakening are the main mechanisms for water induced strain (Fig. 10). For practical analysis the wetting model W4 can be more appropriate to predict the settlement caused by wetting, but careful calibration is needed to obtain the parameters. Note that these wetting models are proposed mainly based on Baud et al. [2], which addressed that the specific surface energy and the frictional coefficient are reduced in the presence of water. In reality, the reduction extent of bond strengths and friction coefficient should be carefully calibrated with experimental results. In the present modeling of wetting–drying cycles, the values of bond strengths and contact friction coefficient are assumed to partially recover back to their original values upon drying. This is just a first approximation, and further experiments and more accurate models are needed to understand the changes of bond strengths and contact friction coefficient during wetting–drying cycles. In nature an acidic solution may accelerate the dissolution rate of minerals, and also the reduction rate of bond strengths. This effect is not considered in the present study as the mechanism is not yet sufficiently clear.

Silvani et al. [51] also studied the effects of wetting time on rockfill creep behavior using particle mechanics method. Even though different wetting models were used in Silvani et al. [51] and this study, respectively, a similar phenomenon found in these two studies is that an instantaneous strain increment was induced when the wetting occurs during the primary creep. Silvani et al. [51] found that the later the water saturation occurs, the lower the additional creep will be, but this study shows that a similar final creep strain was obtained for different wetting time. This difference can be caused by different rockfill aggregate arrangement. In the future, experiments are encouraged to clarify the different wetting effects during primary and secondary creep phases.

5.3. Effects of fouling materials

In addition to normal loading and wetting, other factors may also significantly affect rockfill creep. Effects of fouling materials are briefly discussed below. Clay fouling can affect rockfill mechanical behavior, depending on its amount. Using large-scale triaxial tests, Indraratna et al. [16] showed that a relatively small amount of clay fouling may slightly increase the initial rate of compression, and this can be attributed to the clay-coated aggregates providing a lubrication effect at smaller axial strains. With the increase of fouling, the ballast particles experienced less breakage, attributed to the cushioning effect of clay, which would reduce the high internal contact stresses and the associated attrition of rock particles. Huang et al. [13] and Huang and Tutumluer [14] used experimental methods and discrete element method to characterize the shear strength of fouled road ballast, and showed that fouling materials such as coal dust, plastic clayey soil and mineral filler can generally decrease the shear strength of ballast samples. A similar trend was also found in Indraratna et al. [17]. However, these studies did not pay particular attention to the effects of fouling materials on rockfill creep under dry or wet conditions, which will be studied in the future.

5.4. Implication and limitation

The results show that aggregate crushing in terms of abrasion is the main cause of rockfill creep under dry state, and this suggests that avoiding aggregates with sharp angularities or corners in practice can reduce the creep strain to some extent. This is because the relatively small contact area between sharp corners may easily induce stress concentration and aggregate breakage. The wetting occurring at the primary phase of creep can result in rapid settlement and transition from primary creep to secondary creep, and this suggests that the time gap between the complement of construction and raining season should be considered in design.

Note that two dimensional disk models used in this study refer to a section of rockfill materials, so the width of the model can be understood as the same magnitude as the rockfill aggregate radius. This assumption may or may not represent a strict theoretical plane strain model, but it is helpful to understand the micro-mechanisms that cause rockfill creep. The methodology derived in this study can be easily extended to three dimensional particle mechanics modeling of rockfill creep. It was assumed that both wetting and drying processes occurred instantaneously, but they may need some time for water penetration in practice. This approximation also needs calibration in the future.

6. Conclusion

Particle mechanics method, incorporating bond-aging models and wetting models, is used to understand the rockfill creep mechanisms under dry or wet conditions. The results show that particle mechanics method, not only is a useful tool to capture the main features of rockfill creep, but also can provide insights to the distribution of contact force chains and micro-cracking process, which cannot be easily monitored in experiments. The main concluding remarks are summarized below:

(1) Under dry state, micro-cracking due to the reduction of bond strengths is the main mechanism to generate rockfill creep. In a rockfill specimen where aggregates are irregularly packed, breakage mainly occurs at the angularities or corners of aggregates. Normal stress determines the rates and values of rockfill creep strain.

(2) A wetting-induced reduction of contact friction coefficient (lubrication) is the primary cause of a sudden settlement immediately after wetting, and a wetting-induced reduction of bond strengths (weakening) plays a secondary role in rockfill creep, which may speed up the creep strain evolution.

(3) The earlier the wetting occurs during rockfill creep, the more rapidly the rockfill specimen becomes stable. The wetting-drying cycles can induce strain evolution in a 'stepped' way, but the magnitude of step decreases with the increasing number of wetting–drying cycles.

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