DEM Modeling of Creep Behavior of Rockfill Materials

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ABSTRACT

Rockfill is a common construction material for infrastructure engineering, such as dams, railway and airport foundations, which display a long-term post-construction settlement. The creep behavior of rockfill is dependent on the stress state. Discrete element method (DEM) based on particle mechanics was used to simulate the rockfill creep processes under various stress boundary conditions, in order to understand the mechanisms responsible for rockfill creep. The results showed that the lateral boundary conditions play an important role in determining the rates and magnitudes of rockfill creep strain and the forms of rockfill aggregate breakage, under the case of a constant compressive loading. Under the direct shear testing of a constant normal loading, a relatively small creep (shear displacement) and abrasion occurred under a small magnitude of shear loading, whereas a relatively large creep (shear displacement) and total fragmentation can be induced by a large magnitude of shear loading.

1. INTRODUCTION

Coarse rockfill materials are mainly composed of quarry rock debris or crushed rock fragments, and have been commonly used in many infrastructure projects, such as dams, railway and airport foundations in mountain areas. It is observed that creep settlement at these infrastructures continues for a long period after their construction. Significant post-construction deformation may affect the infrastructure’s serviceability, or even induce engineering disaster. Therefore, the operability and safety of railways and airports impose tight limits for post-construction settlements of the supporting embankments. A number of laboratory or field tests have been carried out to investigate the effects of stress level, initial density, particle characteristics and saturation on the deformation behavior of rockfill materials in the past decade (e.g., McDowell and Khan 2003; Oldecop and Alonso 2007; Huang et al. 2009). However, the nature of rockfill creep and the underlying mechanism of degradation have not been fully understood, mainly due to the difficulty of monitoring the microscopic rockfill response at an individual aggregate level in physical experiments.

The discrete element method (DEM) based on particle mechanics (Potyondy and Cundall, 2004), as an alternative to laboratory or field experiments, has progressed
rapidly over the past decade and been used to examine the micro-mechanism of granular materials subjected to static or dynamic loading, but the use of particle mechanics modeling to study the creep behavior of rockfill materials has been rare in the literature. Kwok and Bolton (2010, 2013) modeled soil creep using particle mechanics method, considering time-dependent contact friction coefficient and bond strength. Tran et al. (2009) and Silvani et al. (2009) incorporated bonding deterioration models into particles mechanics method, in order to simulate the rockfill creep under dry condition. Zhao and Song (2015) used particle mechanics method to simulate the rockfill creep process under dry and wet conditions, respectively. The main objective of this paper is to investigate the rockfill creep behavior subjected to various stress boundary conditions, i.e., biaxial compression or direct shear. This study can be viewed as an extension of DEM modeling performed by Zhao and Song (2015).

2. METHODOLOGY

Two-dimensional (2D) particle flow code, PFC2D, was used in this study. A rockfill aggregate was represented by a 2D dense packing assembly of circular disks of non-uniform sizes, and the disks were bonded in the normal and shear directions at all contacts that possessed finite (normal and shear) stiffness and (tensile and shear) strengths. The contact points between rockfill aggregates were assigned zero bond strength, 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 Potyondy and Cundall (2004). This section mainly focuses on the bond-ageing model and the modeling procedure.

2.1 Bond-ageing model

A few bond-ageing models have been developed in the particle mechanics method, in terms of reducing parallel bond strengths or diameter, (Potyondy 2007; Tran et al. 2009; Silvani et al. 2009). Zhao and Song (2015) compared those bond-ageing models and found that that any one of them can be used to model the rockfill creep in a generic study, if the empirical parameters could be calibrated with experiments. In this paper, bond-ageing model (Eq. (1)) in Tran et al. (2009) was used because of its relatively simple mathematical form and clear physical meaning.

\[
\begin{align*}
\tau_b' = \left\{ \begin{array}{ll}
\tau_b^0 & \beta_i \tau_b^0 > \sigma_n \\
1 - \beta_i \int_{t_0}^{t} \exp \left( \beta_i \frac{\tau_b^0}{\sigma_b^0} - \beta_i \right) dt & \sigma_n^0 \geq \sigma_n \geq \beta_i \tau_b^0 \\
0 & \sigma_n > \sigma_n^0
\end{array} \right.
\end{align*}
\]

\[
\begin{align*}
\sigma_b' = \left\{ \begin{array}{ll}
\sigma_b^0 & \beta_i \sigma_b^0 > \sigma_n \\
1 - \beta_i \int_{t_0}^{t} \exp \left( \beta_i \frac{\sigma_b^0}{\sigma_b^0} - \beta_i \right) dt & \sigma_n^0 \geq \sigma_n \geq \beta_i \sigma_b^0 \\
0 & \sigma_n > \sigma_n^0
\end{array} \right.
\end{align*}
\]
where \( \sigma_b^0 \) and \( \sigma_b^t \) are the short- and long-term normal strength, respectively; \( \tau_b^0 \) and \( \tau_b^t \) 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. The parameter \( \beta_1 \) defines stress threshold of strength degradation (or called activation stress). If the applied normal stress \( \sigma_n \) exceeds \( \sigma_b^0 \), the parallel bond breaks and \( \sigma_b^t \) becomes zero suddenly. When the applied normal stress \( \sigma_n \) is larger than \( \beta_1 \sigma_b^0 \) but smaller than \( \sigma_b^0 \) during the period \([t_0, t]\), the parallel bond strength decreases with time, and the time corresponding to the breakage \((t_f = t - t_0)\) of a given bond under normal stress \( \sigma_n \) can be determined by,

\[
t_f = \frac{1 - \frac{\sigma_n}{\sigma_b^0}}{\beta_1 \exp \left( \frac{\beta_2}{\sigma_b^0 - \beta_1} \right)}
\]

(2)

### 2.2 Modeling procedure

According to the basic specimen-genesis procedure in Potyondy and Cundall (2004), 5000 disks were packed into a square box with a side length of 200 mm to build up rock matrix. 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, and removing the disks located in the voids, a numerical rockfill specimen was generated (Fig. 1a). 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, and numerical biaxial tests showed that the micro-parameters can reflect the nature of rockfill materials.

![Fig. 1 Numerical rockfill specimen consisting of 120 aggregates in a squared box of side length 200 mm and stress boundary conditions](image)

Three scenarios were considered: 1) one-dimensional (1D) compression, 2) biaxial compression and 3) direct shear (Fig. 1b-d). During 1D compression, the normal stress on the upper wall gradually increased to the required values and then remained...
constant using the servo control algorithm, and the lateral and bottom walls kept fixed. For the biaxial compression, the vertical and horizontal stresses on the walls gradually increased to the required values and then remained constant using the servo control algorithm. During the direct shear test, the normal and shear stresses on the upper box gradually increased to the required values and then remained constant using the servo control algorithm, and the lower box kept fixed. Once bond degradation became active, micro-cracking in rockfill aggregates could be induced and macroscopic deformation of rockfill specimen occurred. The breakage of rockfill aggregates, deformation of the rockfill specimens and bond force chains in the rockfill specimen were monitored during the creep test.

Table 1 Micro-parameters for the rockfill agglomerates.

<table>
<thead>
<tr>
<th>Parameter (unit)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of balls</td>
<td>5 000</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>2 230</td>
</tr>
<tr>
<td>Contact modulus</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 β₁, β₂ and β₃</td>
<td>0.4, 40 and 5×10⁻¹¹</td>
</tr>
</tbody>
</table>

3. RESULTS

3.1 Rockfill creep under 1D compression
The creep strain-time curve under a constant normal stress of 1.14 MPa is presented in Fig. 2a, and both primary creep and secondary creep phases were observed. Since this scenario has been studied in Zhao and Song (2015), only the important findings are summarized below. The higher the normal stress was, the larger were the creep strain rate during primary creep phase and the eventual creep strain. The reduction of parallel-bond strength with time and the formation of micro-cracks were the main mechanism of producing creep. Rockfill aggregate breakage occurred in the form of abrasion (angularity/corner breakage).

3.2 Rockfill creep under biaxial compression
A constant vertical stress (σᵥ) of 1.14 MPa was applied on the top and bottom boundaries. The horizontal stress (σₓ) applied on the left and right lateral boundaries varied from 0.34 to 0.74 MPa, so that a stress ratio, defined as K=σₓ/σᵥ, increased from K= 0.30 to 0.65. The axial and lateral strain-time curves under different stress ratios are plotted in Fig. 2b-d. When the horizontal stress was low (e.g., 0.34 MPa), an increasing
positive lateral strain with time was observed, which means that the left and right lateral walls moved outwards during rockfill creep. With the horizontal stress increasing to 0.54 MPa, both axial and lateral strains decreased. When the horizontal stress further increased to 0.74 MPa, a typical creep curve including primary, secondary and tertiary creep phases was found. Examining the rockfill creep behavior under one dimensional and biaxial compression indicates that the lateral boundary conditions is a critical factor that not only determines the absolute value of creep strain, but also affects the rate of creep strain evolution. Under the case of a low confining stress, the moving lateral walls reduced the stress levels in the rockfill specimen, and abrasion is the main form of rockfill aggregate breakage (Fig. 3). Under the case of a medium confining stress, the local bond degradation cannot induce significant stress redistribution in the rockfill specimen, so the magnitude of rockfill creep is the smallest (Fig. 3). Under the case of a high confining stress, local stress concentrations continuously occur in the rockfill specimen and induce the significant rockfill creep, and total fragmentation (particle splitting) can occur in some rockfill aggregates in addition to abrasion (Fig. 3).

![Fig. 2 Rockfill deformation under one dimensional (a) and biaxial (b-d) compression](image)

3.3 Rockfill creep under direct shear

A constant normal stress ($\sigma_y$) of 1.14 MPa was applied on the upper shear box. The constant shear stress ($\sigma_x$) applied on the upper shear box varied from 0.27 to 0.47 MPa. The normal and shear displacement-time curves under different shear stresses are plotted in Fig. 4. When the shear stress was low (e.g., 0.27 and 0.32 MPa), rockfill creep mainly occurred in the form of vertical deformation, without significant shear displacements. With the shear stress increasing to 0.42 MPa, both normal and shear displacements became significant. When the shear stress further increased to 0.47 MPa, the magnitude of shear displacement increased compared with that under the
shear stress of 0.42 MPa, but the magnitude of normal displacement was approximately similar to that under the shear stress of 0.42 MPa. At $t = 40$ minutes, a slight dilation was observed under the shear stress of 0.47 MPa, which indicates the occurrence of sliding between rockfill aggregate close to the shear plane.

$$\sigma_x/\sigma_y = 0.30 \quad \sigma_x/\sigma_y = 0.47 \quad \sigma_x/\sigma_y = 0.65$$

![Bond force distribution](image1)

![Micro-crack distribution](image2)

Fig. 3 Bond force and micro-crack distribution in rockfill specimens under biaxial compression

![Rockfill displacements](image3)

Fig. 4 Rockfill displacements under direct shear
Using the bond force and micro-crack distributions under shear stresses of 0.27 and 0.47 MPa to explain the microscopic mechanism responsible for rockfill creep under direct shear (Fig. 5). Under the case of a low shear stress which cannot overcome the reducing shear resistance at the shear plane due to the local bond degradation, shear displacement is relatively small and abrasion is the main form of rockfill aggregate breakage. Whereas, when the shear stress was sufficiently high, the local bond degradation can induce significant shear displacements, shear contractions or (possible) dilation. Total fragmentation (particle splitting) can also occur in some rockfill aggregates in addition to abrasion.

![Figure 5](image1.png)

**Fig. 5** Bond force and micro-crack distribution in rockfill specimens under direct shear

4. CONCLUSIONS

Particle mechanics method, incorporating bond-aging models, was used to study the rockfill creep mechanisms under various stress boundary conditions, i.e., 1D compression with fixed lateral boundaries, biaxial compression and direct shear. The results showed 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 force chains and micro-cracking process, which cannot be easily monitored in laboratory or field experiments. The main concluding remarks are summarized below:

(1) Under the case of a constant compressive loading, the lateral boundary condition play an important role in determining the rates, values of rockfill creep strain and the form of rockfill aggregate breakage. A critical value of stress ratio between the
horizontal and vertical stresses induces a relatively small creep strain.

(2) Under the case of a constant normal loading, the magnitude of shear loading can determine the magnitude of shear displacement, as well as the form of rockfill aggregate breakage.

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