Evaluation of time-dependent behavior of interface between rockfill and bed rock using a large-scale shear testing apparatus

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ABSTRACT

Shear creep of interface between rockfill and the bed rock underneath is studied. A test apparatus is designed and manufactured for the purpose of present research, whose direct shear cell consists of an upper box for rockfill, and a nether box for rock slate, longer than the upper one to keep the contact area constant during shearing. The normal stress is kept constant in the experiment, while the shear load is applied stepwise. The tangential and normal displacements are recorded during the tests. Creep behavior of such interface is discussed through the analysis of the test results. On the basis of experimental research, an elastic-viscoplastic model is preliminarily proposed for describing the shear creep behavior of interface.

1. INTRODUCTION

With the development of the Chinese economy, many engineering projects, such as highways, airports etc., have been constructed in the mountainous regions of west China. In order to have a suitable piece of land for the engineering projects, one has to cut the peak and fill the valley in the mountains so as to form a high-filled ground where the filling material is often broken rock form the cut mountain peak. It is noted from the past engineering practice that such a high-filled ground often shows time dependent deformation behaviors. In order to evaluate its stability and post construction settlements, studies are required both for the filled body and for the interface between the rockfill and the bed rock. Especially the mechanical characteristics of inclined interfaces are of great importance to the long-term deformation and stability of the high-filled ground. This research emphasizes on the interface between filling material and original rock foundation.

Previously, the static and dynamic mechanical characteristics of soil-structure or soil-rock interfaces have been investigated by many researchers. Clough & Duncan

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(1971) started experimental researches in early years, and suggested a hyperbolic relation for the stress and shear strain, which had been widely adopted. Yin & Zhu et al. (1995) conducted large scale tests, with a viewer inside the apparatus, to investigate the development of shear failure in the soil layer neighboring the interface. Zhang & Zhang (2007), Zhang & Yu et al. (2008), and Feng (2012) developed a large apparatus for testing the deformation and strength of interfaces between rockfill and structural panels.

The long-term deformation and strength characteristics have also been paid attention. A small scale direct shear instrument was set up by Koerner and Soong et al. (2001) to study the contact interface of sand and geotextiles. And a 5-order viscoelastic Kelvin model was suggested for simulating the interface behavior. Li and Liu et al. (2008) conducted shear creep tests of sand rock joint planes and used the Burgers model to describe rock joint shear behavior. Due to the limitation of testing apparatus, the shear stresses of these tests are less than 100 kPa. As a result, the creep behaviors under high stresses cannot be reflected. Even though greater loads can be provided by the large apparatus for static and dynamic mechanical tests, the working duration is limited.

Previous researches are still not enough to understand the interface behaviors in high-fill projects. In order to investigate the long-term behavior of interface between rockfill and bed rock, a large-scale shear testing apparatus has been manufactured by the authors. Shear creep tests are conducted with the apparatus, using the rockfills of Chong-Qing Airport.

2. TESTING APPARATUS

A new testing apparatus is designed and manufactured for the purpose of present research, as shown in Fig. 1. The direct shear cell consists of an upper box for rockfill, with the dimensions of 20cm x 20cm x 10cm, and a nether box for rock slate, with the inner dimensions of 25cm x 20cm x 10cm, which is longer than the upper one to keep the contact area constant during shearing. The overall size of the apparatus is 2.4m x 0.5m x 1.45 m.
Loads are applied via a combination of levers and chain wheels. The apparatus could provide a normal compressive stress up to 1.46 MPa and a tangential shear stress up to 1.34 MPa. The nether box is designed to move right when the shear stress applied, while the upper box is fixed. The boxes are specially designed to avoid rotation during the test.

3. RESULTS AND DISCUSSIONS

Shear creep tests are conducted with the apparatus. The rockfills from Chongqing Airport are used. The grains are mainly shivers of sand stones and mud stones, with the size of grains in the sample lying between 1 mm ~ 2 cm. Air dried materials are enclosed into the upper box and compacted layer by layer. The final volumetric weight of the rockfill sample is 17.6~17.7 kN/m$^3$. The result of a staged loading test is presented here.

The normal load $\sigma_n=523$ kPa was first applied and was kept constant during the whole test. After vertical deformation became stable, shear loads were applied stepwise. The shear stresses were $\tau=110$ kPa, 184 kPa, 258 kPa and 333 kPa, kept for 90 h, 100 h, 140 h and 145 h respectively. After the creep test, the shear stress was increased till the failure of the interface, in order to measure its peak strength. The maximum shear stress was $\tau_f=342$ kPa, and the corresponding friction angle is $\phi=33.2^\circ$.

During the processes of shear loading and shear creep, the horizontal displacement of the nether box $u_h$ and the vertical displacement at the center of the rigid cap on top of the upper box $u_v$ were recorded (see Fig. 2). The average volumetric strain $\varepsilon_v$ of the sample is proportional to $u_h$ and the shear strain $\varepsilon_s$ is proportional to $u_v$. As can be seen from the results, $u_h$ was positive while $u_v$ was negative, which indicated the phenomenon of shear contraction and the dilatancy angle $\psi<0$.
In creep tests, the displacements increase very quickly after each loading step, then followed by a lower rate creep process. A unit time (e.g. 1 min, 1 h or 1 day) is usually adopted to partition the instant deformation and creep deformation. At 1 min after loading, the horizontal displacement rate has decreased to a value lower than 0.06 mm/min, which is acceptable as a creep rate. So, 1 min is adopted in this case. To better present the creep process, the incremental deformations from 1 min after loading are calculated and shown in Tab. 1 and Fig. 3. The relation of shear stress $\tau$, horizontal displacement $u_h$ and vertical displacement $u_v$ is presented in Fig. 4.

<table>
<thead>
<tr>
<th>$\tau$ (kPa)</th>
<th>Horizontal deformation $\Delta u_h$ (mm)</th>
<th>Vertical deformation $\Delta u_v$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1min</td>
<td>10min</td>
</tr>
<tr>
<td>110</td>
<td>0.000</td>
<td>0.123</td>
</tr>
<tr>
<td>184</td>
<td>0.000</td>
<td>0.128</td>
</tr>
<tr>
<td>258</td>
<td>0.000</td>
<td>0.162</td>
</tr>
<tr>
<td>333</td>
<td>0.000</td>
<td>0.200</td>
</tr>
</tbody>
</table>
The following phenomena are concluded from this experiment with constant vertical normal stress $\sigma_n$ and staged shear stress $\tau$:

i) The absolute value of shear deformation and volumetric change increases with shear stress.

ii) The higher shear stress is, the larger shear creep rate and shear creep strain will be. However, the volumetric creep strain changes little with shear stress.

iii) The absolute value of the ratio of vertical displacement to horizontal displacement $|v_\tau / u_h|$ decreases with shear stress, from 0.35 under a low stress level to 0.13 under a high stress level, which means the absolute value of the dilatancy angel $|\nu|$ decreases with shear stress.

iv) Under a given shear stress, $|v_\tau / u_h|$ increases with time. As the creep deformation is plastic deformation, the $du_\tau / du_h$ in a time interval $\Delta t$ indicates the instant dilatancy angle. So, in the creep process, $|\nu|$ increases with time. More attention should be paid to this special $|\nu|$-time relation in the future.

4. MODELING SHEAR CREEP BEHAVIOR OF INTERFACE

Previous interface models can describe time-independent behaviors of interfaces very well, but few can reflect the time-dependent behaviors. Recently, the authors have proposed an elastic-viscoplastic (EVP) constitutive model for the creep of rockfills. Here, the same concept is used to develop a shear creep model for the interface. The shear stress-shear strain-time relation is the main concern of this paper, and volumetric change is not discussed here.

The strain of the interface is defined as the average deformation in a certain thickness $h$. The shear strain and volumetric strain are:
In this test, the height of the sample in the upper box is 10 cm, 5 times of the largest grain diameter. \( h \) is defined to be 10 cm.

The normal stress of the interface is denoted as \( \sigma_n \), and shear stress/tangential stress denoted as \( \tau \). When subjected to a loading process named static loading, in which the loading rate \( \dot{\varepsilon}_s \to 0 \), the peak shear stress \( \tau_f \) is:

\[
\tau_f = \sigma_n \times \tan \varphi
\]

where \( \varphi \) is the peak friction angle for static loading. It has been shown by experiments show that the strength is a function of \( \sigma_n \):

\[
0 \leq \varphi - \Delta \varphi \log(\sigma_n / p_{ref})\leq 0
\]

where \( \varphi_0 \) and \( \Delta \varphi \) are material parameters, and \( p_{ref} = 100 \text{kPa} \).

In static loading, the shear strain \( \varepsilon_s \) and shear stress \( \tau \) fits a hyperbolic relation:

\[
\tau = \min \left( \frac{\varepsilon_s}{a + b\varepsilon_s}, \tau_f \right)
\]

in which \( a = 1 / E_s \), and \( E_s \) is the initial tangential modulus, dependent with normal stress \( E_s = E_s^{ref} (\sigma_n / p_{ref})^w \), \( b = R_f / \tau_f \), and \( R_f \) is the failure ratio.

It is assumed by the model that under a given shear rate \( \dot{\varepsilon}_s \), the stress-strain relation is also hyperbolic:

\[
\tau = \min \left( \frac{\varepsilon_s}{a + b\varepsilon_s}, \tau_f \right) \times \left[ 1 + \zeta \ln \left( 1 + \frac{\dot{\varepsilon}_s}{\dot{\varepsilon}^*} \right) \right]
\]

where \( \dot{\varepsilon}^* \) and \( \zeta \) are material parameters. They can be valued from constant rate loading tests or by fitting shear creep test results.

By combining the relations described in Eqs. (4) and (5) with the EVP framework, the relation between incremental strain and incremental stress can be derived with approximation:

\[
\dot{\varepsilon}_s \approx \dot{\varepsilon}^* \left[ \frac{1}{\tau} \left( 1 + \frac{b}{E_s^{ref}} \right) - 1 \right]
\]

where \( b = \min \left( 1 / \tau - a / \varepsilon_s, b \right) \) and \( b = R_f / \tau_f \), \( E_s^{ref} \) is the unloading-reloading modulus, dependent with normal stress \( E_s^{ref} = E_s^{ref} (\sigma_n / p_{ref})^w \).

As for the creep process with constant stress \( \dot{\varepsilon}_s \equiv 0 \), Eq. (6) is simplified to:

\[
\dot{\varepsilon}_s \approx \dot{\varepsilon}^* \left( \frac{1}{\tau} \left( 1 + \frac{b}{E_s^{ref}} \right) - 1 \right)
\]

By solving this differential equation, we get an approximated relation of strain and time as follow:

\[
\varepsilon_s \approx \left[ \text{Lambert} W \left( \exp((k - A t)B^2 - 1) \right) + 1 \right] / B + c
\]

in which \( A = \frac{a \dot{\varepsilon}^*}{\delta b} \) is independent with shear stress and \( B = \frac{1 / \tau - b}{a} \) decreases when \( \tau \) increases. \( k \) and \( c \) are constants. The \textit{Lambert} \textit{W} function, also called the \textit{product log function} or the \textit{omega function}, is the \textit{inverse relation} of the function \( f(z) = z \cdot \exp(z) \) where \( \exp(z) \) is the exponential function and \( z \) is any complex number.
Eq. (7) is then used to fit creep tests presented before to get $\dot{\varepsilon}/\delta = 0.0167 \text{ h}^{-1}$. Due to the lack of static loading test results, it is assumed that $\tau_f = 342 \text{kPa}$ and $\varphi = 33.2^\circ$. Other parameters concluded from the test include: $E_i = 28571 \text{kPa}$, $R_f = 0.86$, $E_{\omega} = 5 E_i$. The differential equation of Eq.(6) is programed in Matlab to calculate the deformation in the whole test. When $\delta = 0.0033$ and $\dot{\varepsilon} = 5.5 \times 10^{-5} \text{h}^{-1}$, the model can fit the trend of the strain-time relation (see Fig. 5).

5. CONCLUSIONS

The creep behavior of the interface between the rockfill and bed rock is investigated. A large-scale shear testing apparatus is manufactured for the research of interface behavior. The Rockfills from Chong-Qing airport and bluestone slates are used in the experimental research.

The laws for shear creep and volumetric creep under constant normal stress and staged shear stress are concluded from tests. A shear creep model based on the elastic-viscoplastic framework is preliminarily proposed and testified by the experiment. Sequential studies are still in progress.

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REFERENCES


