The 2016 World Congress on
Advances in Civil, Environmental, and Materials Research (ACEM16)
Jeju Island, Korea, August 28-September 1, 2016

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

*Yufei Kong[1], Tianliang Zheng[2], Ming Xu[3] and Erxiang Song[4]

[1], [2], [3], [4] *Department of Civil Engineering, Tsinghua University, Beijing 100084, China*
[1] *tztxkyf@163.com*
[4] *songex@tsinghua.edu.cn*

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

[1] Ph.D. candidate
[4] Corresponding author, Professor

(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.

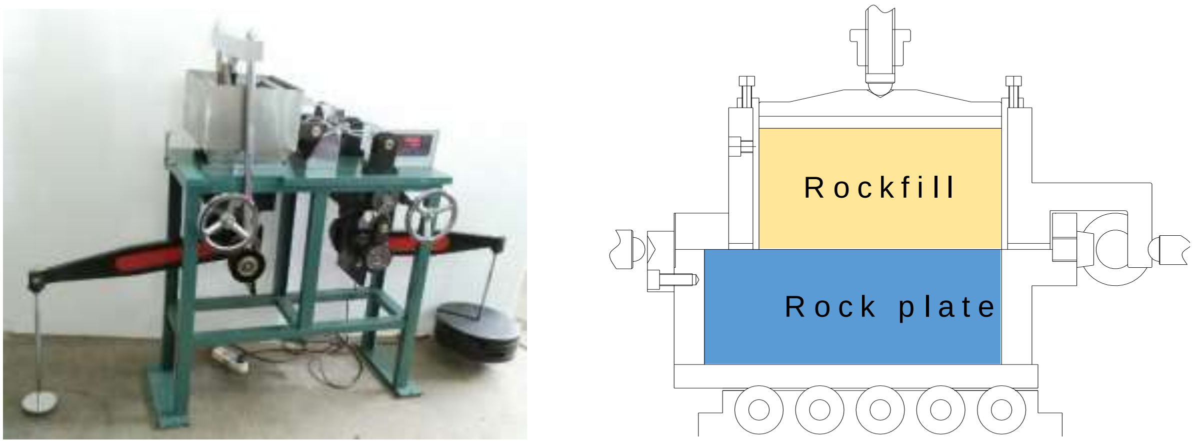


Fig. 1 Photo of the testing apparatus and sketch of the shear box

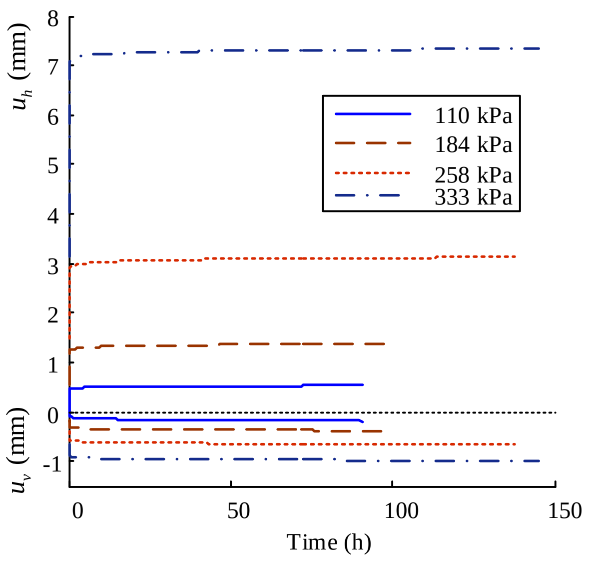
Loads are applied via a combination of levers and chain wheels. The apparatus could provide a normal compressive stress up to 1.46MPa and a tangential shear stress up to 1.34MPa. The nether box is designed to move right when the shear stress applied, while the upper box is fixed. The boxes are specially designed to avoid rotation during the test.

3. RESULTS AND DISCUSSIONS

Shear creep tests are conducted with the apparatus. The rockfills from Chong-Qing Airport are used. The grains are mainly shivers of sand stones and mud stones, with the size of grains in the sample lying between 1mm ~ 2cm. 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 σ_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 τ=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 τ_f=342 kPa, and the corresponding friction angle is φ =33.2°.

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* ε_v of the sample is proportional to u_h and the *shear strain* ε_s is proportional to u_h. 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 $\psi < 0$.



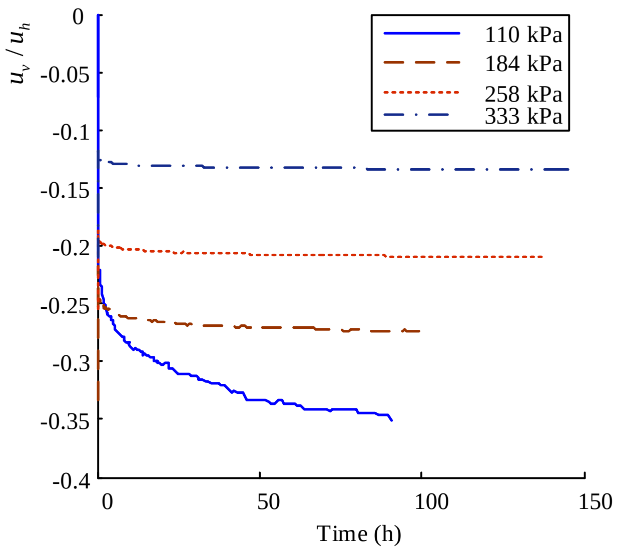


Fig. 2 u_h, u_v and u_v/u_h versus time under different shear stresses

In creep tests, the displacements increases 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 0.06mm/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 τ, horizontal displacement u_h and vertical displacement u_v is presented in Fig. 4.

Tab. 1 Incremental deformation Δu_h and Δu_v versus time from t=1min after loading

τ (kPa)	Horizontal deformation Δu_h (mm)						Vertical deformation Δu_v (mm)					
	1min	10min	1h	10h	30h	90h	1min	10min	1h	10h	30h	90h
110	0.000	0.123	0.154	0.186	0.202	0.217	0.000	-0.045	-0.071	-0.105	-0.123	-0.147
184	0.000	0.128	0.184	0.244	0.271	0.301	0.000	-0.043	-0.068	-0.100	-0.116	-0.131
258	0.000	0.162	0.251	0.348	0.392	0.432	0.000	-0.043	-0.072	-0.109	-0.127	-0.145
333	0.000	0.200	0.300	0.407	0.454	0.497	0.000	-0.047	-0.083	-0.123	-0.144	-0.163

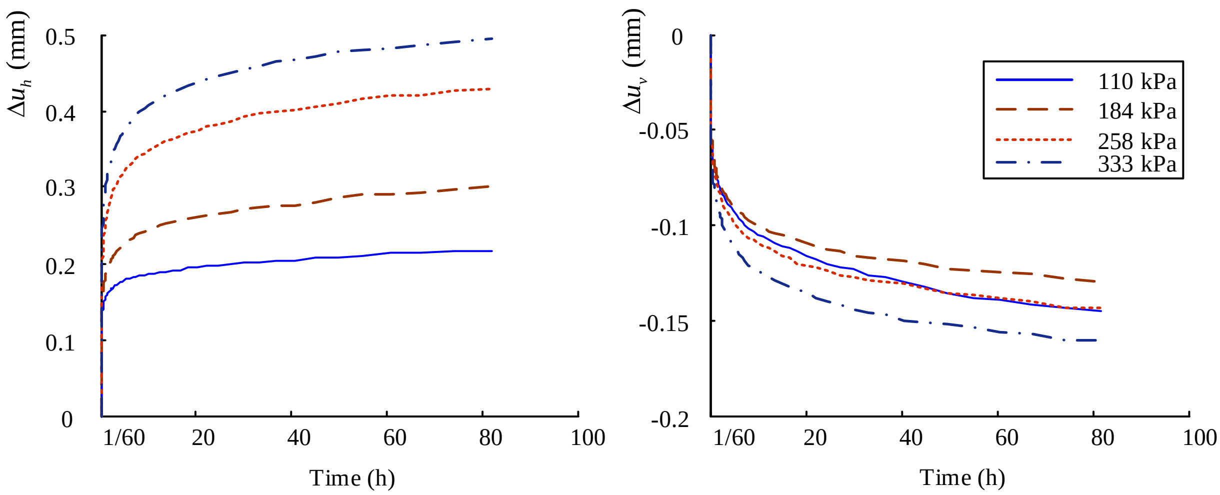


Fig. 3 Incremental deformation Δu_h and Δu_v versus time from 1min after loading

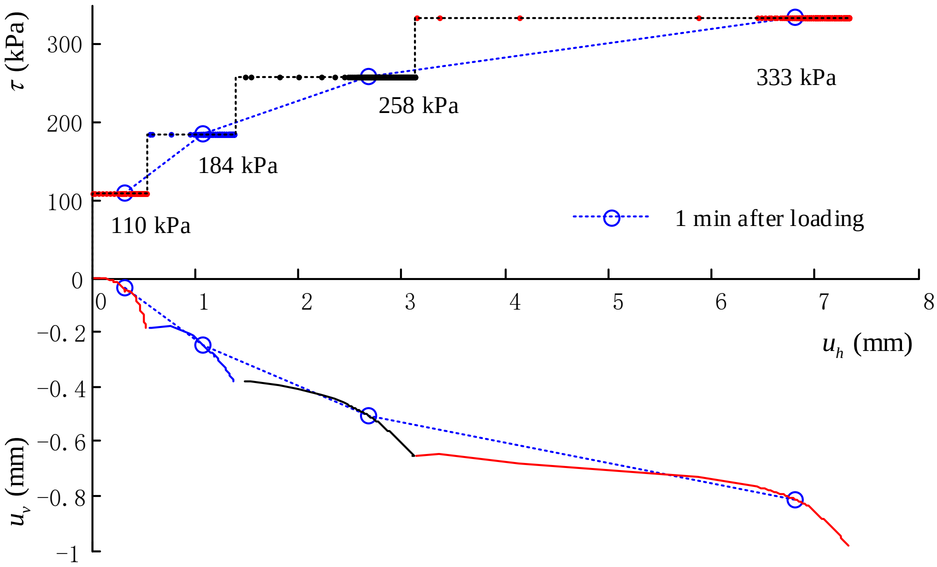


Fig. 4 τ - u_h relation and u_v - u_h relation in the experiment

The following phenomena are concluded from this experiment with constant vertical normal stress σ_n and staged shear stress τ :

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 $|u_v / u_h|$ 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 $|\psi|$ decreases with shear stress.

iv) Under a given shear stress, $|u_v / u_h|$ increases with time. As the creep deformation is plastic deformation, the $\mathrm{d}u_v / \mathrm{d}u_h$ in a time interval $\mathrm{d}t$ indicates the instant dilatancy angle. So, in the creep process, $|\psi|$ increases with time. More attention should be paid to this special $|\psi|$-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:

$$\varepsilon_v = u_v / h \,, \varepsilon_s = u_h / h \tag{1}$$

In this test, the height of the sample in the upper box is 10cm, 5 times of the largest grain diameter. h is defined to be 10 cm.

The normal stress of the interface is denoted as σ_n, and shear stress/ tangential stress denoted as τ. When subjected to a loading process named *static loading*, in which the loading rate $\dot{\varepsilon}_s \to 0$, the peak shear stress τ_f is:

$$\tau_f = \sigma_n \times \tan\varphi \tag{2}$$

where φ is the peak friction angle for static loading. It has been shown by experiments show that the strength is a function of σ_n:

$$\varphi = \varphi_0 - \Delta\varphi \lg(\sigma_n / p^{ref}) \tag{3}$$

where φ_0 and $\Delta\varphi$ are material parameters, and p^{ref} =100kPa.

In static loading, the shear strain ε_s and shear stress τ fits a hyperbolic relation:

$$\tau = \min\left(\frac{\varepsilon_s}{a + b\varepsilon_s}, \tau_f\right) \tag{4}$$

in which $a = 1/E_i$, and E_i is the initial tangential modulus, dependent with normal stress $E_i = E_i^{ref}(\sigma_n / p^{ref})^m$. $b = R_f / \tau_f$, 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:

$$\tau = \min\left(\frac{\varepsilon_s}{a + b\varepsilon_s}, \tau_f\right) \times \left[1 + \zeta \ln\left(1 + \frac{\dot{\varepsilon}_s}{\dot{\varepsilon}^*}\right)\right] \tag{5}$$

where $\dot{\varepsilon}^*$ and ζ 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 :

$$\dot{\varepsilon}_s \approx \dot{\tau} / E_{ur} + \dot{\varepsilon}^*[e^{\frac{1}{\delta}(\frac{b}{b'}-1)} - 1] \tag{6}$$

where $b' = \min(1/\tau - a/\varepsilon_s, b)$ and $b = R_f / \tau_f$. E_{ur} is the unloading-reloading modulus, dependent with normal stress $E_{ur} = E_{ur}{}^{ref}(\sigma_n / p^{ref})^m$.

As for the creep process with constant stress $\dot{\tau}=0$, Eq. (6) is simplified to $\dot{\varepsilon}_s \approx \dot{\varepsilon}^*[e^{\frac{1}{\delta}(\frac{b}{b'}-1)} - 1]$. By solving this differential equation, we get an approximated relation of strain and time as follow:

$$\varepsilon_s \approx \left[\mathrm{LambertW}\left(\exp((k - At)B^2 - 1)\right) + 1\right] / B + c \tag{7}$$

in which *A* and *B* are related to material properties and stress conditions. $A = \frac{a\dot{\varepsilon}^*}{\delta b}$ is independent with shear stress and $B = \frac{1/\tau - b}{a}$ decreases when τ increases. *k* and *c* are constants. The *Lambert W* function, also called the *product log function* or *the omega function*, is the *inverse relation* of the function $f(z) = z \cdot \exp(z)$ where $\exp(z)$ is the exponential function and z is any complex number.

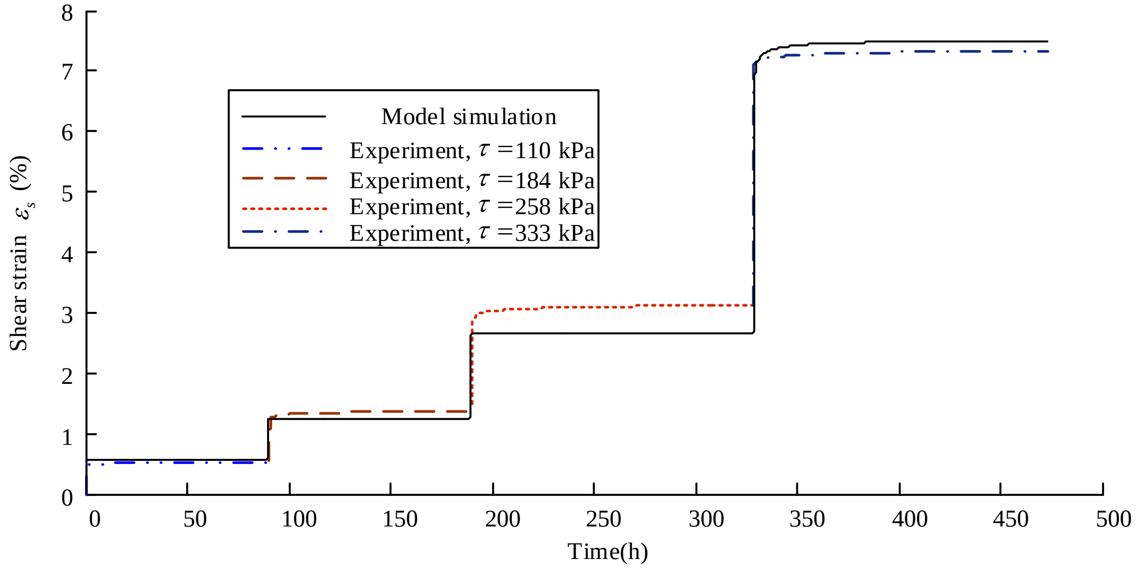


Fig. 5 Simulation of the shear strain-time curve in the whole test with the proposed shear creep model

Eq. (7) is then used to fit creep tests presented before to get $\dot{\varepsilon}^* / \delta$ =0.0167 h^{-1}. Due to the lack of static loading test results, it is assumed that τ_f =342kPa and φ=33.2°. Other parameters concluded from the test include: E_i =28571 kPa, R_f =0.86, E_{ur} =5 E_i. The differential equation of Eq.(6) is programed in Matlab to calculate the deformation in the whole test. When δ =0.0033 and $\dot{\varepsilon}^*$ =5.5×$10^{-5}$$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.

ACKNOWLEDGEMENTS

The work reported in this paper is financially supported by the *National Key Fundamental Research and Development Program of China* (Project No. 2014CB047003).

REFERENCES

Feng, D. (2012). "Three-dimensional constitutive laws, mechanism and model of gravel-structure interfaces." Tsinghua University, Ph. D thesis.

Koerner, R. M. and Soong, T. Y., et al. (2001). "Creep testing and data extrapolation of reinforced GCLs." GEOTEXT GEOMEMBRANES, 19 (7): 413-425.

Li, P. and Liu, J., et al. (2008). "Research on effects of water content on shear creep behavior of weak structural plane of sandstone." ROCK SOIL MECH, 29 (07): 1865-1871.(in Chinese)

Yin, Z. and Zhu, H., et al. (1995). "A study of deformation in the interface between soil and concrete." COMPUT GEOTECH, 17 (1): 75-92.

Zhang, B. and Yu, Y., et al. (2008). "Simple shear test for interfaces between core and filter soils in rock-fill dams." GEOTECH TEST J, 31 (3): 516.

Zhang, G. and Zhang, J. (2007). "Three-dimensional model of interface between structure and coarse grained soil." ROCK SOIL MECH, 28 (02): 288-292. (in Chinese)