Element tests on hydraulic-mechanical behavior of saturated–unsaturated landslide dam materials

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\textbf{ABSTRACT}

Stability of landslide dam is of great concern worldwide. Geomaterials of a landslide dam, a natural dam, are usually at unsaturated state, which requires a saturated/unsaturated constitutive model to describe the hydro-mechanical behavior of the landslide dam materials (LDM). Study (Xiong et al., 2018) has been done on the failure mechanism under seepage loadings both in model tests and numerical simulations, while the element behavior of LDM is still unclear. In this paper, large-scale saturated triaxial compression tests under undrained condition, water retention test and unsaturated triaxial compression test under undrained/unvented condition were conducted on four kinds of LDM. Results of saturated large-scale triaxial tests show the shear stress ratio at critical state with a gap-graded mixture is the largest, which indicates the landslide dam made of this material is the most stable. Water retention curve (WRC) of LDM is obtained in water retention tests. Hysteresis of WRC varies with different grain size distributions. Unsaturated triaxial test results in four different LDM show that the strength of the materials increases with the increase of suction and mean net stress, and the same tendency in the change of the volumetric strain can be observed.

\textbf{Keywords:} landslide dam, saturated–unsaturated, triaxial compression test, water retention test

\textbf{1 INTRODUCTION}

Landslide dams are the blockages of the river channel by an earth or rock mass and are widely existing around the world. Failure of this kind of natural dam causes huge damage to the downstream area (Wu et al., 2014). Therefore, investigations on the stability of the landslide dam are undoubtedly important for protecting the lives and properties. Overtopping, piping and slope failure are the major causes of the landslide dam failure (Costa and Schuster, 1988). Due to the water level increase in landslide lake, landslide dams are under seepage loadings, which may further induce the piping and overtopping failure. Therefore, study on the hydro-mechanical behavior of LDM under seepage loadings is critical in understanding the stability of landslide dams.

Most of the geomaterials of the landslide dams are at unsaturated state, which results in the change on the degree of saturation under seepage loadings. Therefore, rational saturated/unsaturated constitutive model and suitable material parameters are indispensable in describing the hydro-mechanical behavior of LDM. Zhang and Ikariya (2011) proposed a saturated/unsaturated constitutive model, which has been utilized in previous study (Xiong et al., 2018) on the failure mechanism under seepage loadings. However, it is noteworthy that the material parameters under saturated-unsaturated conditions were lacking verification (Xiong et al., 2018). Therefore, element tests under saturated/unsaturated conditions need to be performed in order to obtain the material properties to quantitatively describe the material behavior under seepage loadings.

In this paper, a series of element tests was conducted to obtain the hydro-mechanical properties of LDM. At first, large-scale saturated triaxial compression tests were performed under undrained condition on four kinds of LDM. Then water retention tests were applied on two kinds of LDM in order to obtain the water retention curves (WRC). Finally, unsaturated triaxial compression tests were followed on one kind of LDM.

\textbf{2 TEST MATERIALS}

Landslide dams usually consist of various kinds of materials and the variation in grain size is also great. In order to obtain the typical LDM, four accumulative grain size distribution curves were chosen from the research by Casagli et al. (2003) and represented (1) Sand, (2) well-graded mixture, (3) gap-graded mixture and (4) coarse mixture. The accumulative grain size distribution curves chosen are shown in Fig. 1. The material used in all the tests was silica sand with different particle sizes.
Particles smaller than 40 mm were used in the large-scale triaxial compression tests on well-graded, gap-graded and coarse materials, while particles smaller than 2 mm were used in the water retention tests, saturated triaxial compression tests on sand material and unsaturated triaxial compression tests on gap-graded material. The physical properties of LDM are listed in Table 1.

3 TEST APPARATUS

3.1 Large-scale triaxial compression test apparatus

The saturated large-scale triaxial compression test apparatus used in the study is shown in Fig. 2. Saturated triaxial compression tests on well-graded material, gap-graded material and coarse material were conducted on this apparatus.

3.2 Saturated/unsaturated triaxial test apparatus

The maximum grain size of sand material is 2 mm, therefore the saturated/unsaturated triaxial test apparatus, shown in Fig. 3, can be used to conduct the saturated triaxial compression tests on sand material. Porous stone was utilized in saturated triaxial compression test, while it was changed to a ceramic disk with high air entry value in unsaturated triaxial compression test in order to control the suction.

3.3 Saturated/unsaturated oedometer test apparatus

The water retention tests were conducted on a saturated/unsaturated oedometer apparatus shown in Fig. 4. Axis-translation method is applied to control the suction by the utilization of a ceramic disk with high air entry value.
4 TEST METHODS

4.1 Saturated triaxial test

Specimens made of silica sand for large-scale saturated triaxial compression test were prepared by static compaction layer by layer with a hammer. 15 times of compaction were applied to the specimens with 300 mm in diameter and 600 mm in height, while 8 times of compaction were utilized on specimens with 300 mm in diameter and 300 mm in height. Sizes of the specimen under different confining stress are listed in Table 2. The initial moisture contents \( w_0 \) were 5 %, 14 % and 3 % for well-graded material, gap-graded material and coarse material, respectively. CO2 and back pressure of 200 kPa were applied to reach the saturated state and the saturation was over 0.92 in all cases. Then the specimens were consolidated under  the same confining stress but at different suction levels firstly. Then the specimens were consolidated under the target confining stress. A constant axial strain loading condition was adopted and the loading rate was 0.005 %/min in all cases.

| Material       | Confining stress, \( \sigma_3 \) [kPa] | Specimen size | Void ratio, \( e_0 \) before compression | Void ratio, \( e_0 \) right after preparation |
|----------------|----------------------------------------|---------------|------------------------------------------|--------------------------------------------|
| Sand           | 50/100/200                             | 50 × 100      | 0.555                                    | 0.536                                       |
| Well-graded    | 50                                     | 300 × 300     | 0.594                                    | 0.552                                       |
| Gap-graded     | 100/200/400                            | 300 × 600     | 0.403                                    | 0.348                                       |
| Coarse         | 100/200/400                            | 300 × 600     | 0.352                                    | 0.302                                       |

Table 2. Type of specimen size and confining stress in saturated triaxial compression tests.

Specimens of sand material were prepared by water pluviation method and initial void ratio, \( e_{0i} \), was targeted at 0.6. The specimen sizes are given in Table 2. The initial saturation of the specimen was over 0.98 in all cases. After being prepared, the specimens were consolidated under back pressure of 200 kPa. A constant axial strain loading rate of 0.005 %/min was adopted under the undrained condition. Table 3 gives the information on the void ratio at different test stages.

4.2 Water retention test

The specimens for the water retention tests were 60 mm in diameter and 10 mm in height and the initial water contents, \( w_0 \), of 6 % and 14 % were adjusted for well-graded material and gap-graded material, in order to achieve the initial void ratio, \( e_{0i} \), of 0.73 and 0.51, respectively. The loading paths of the water retention tests are shown in Fig. 5. The vertical net stress was 50 kPa in all the tests.

| Material       | Confining stress, \( \sigma_3 \) [kPa] | Void ratio, \( e_0 \) before preparation | Void ratio, \( e_0 \) right after preparation |
|----------------|----------------------------------------|------------------------------------------|--------------------------------------------|
| Sand           | 50                                     | 0.576                                    | 0.526                                       |
| Well-graded    | 100/200/400                            | 0.403                                    | 0.348                                       |
| Gap-graded     | 100/200/400                            | 0.352                                    | 0.302                                       |
| Coarse         | 100/200/400                            | 0.302                                    | 0.288                                       |

Table 3. Void ratio at different loading stages.

Specimens of sand material were prepared by water pluviation method and initial void ratio, \( e_{0i} \), was targeted at 0.6. The specimen sizes are given in Table 2. The initial saturation of the specimen was over 0.98 in all cases. After being prepared, the specimens were consolidated under back pressure of 200 kPa. A constant axial strain loading rate of 0.005 %/min was then adopted under the undrained condition. Table 3 gives the information on the void ratio at different test stages.

4.3 Unsaturated triaxial test

Specimens made of silica sand with gap-graded mixture were prepared by water pluviation method and initial void ratio was targeted at 0.75. Particles with size over 2 mm were sieved. The specimens were 50 mm in diameter and 100 mm in height. The stress paths of all the cases are shown in Fig. 6. Specimens were consolidated under the same confining stress but at different suction levels firstly. Then the specimens were consolidated at the final confining stress, followed by the shearing stage under undrained/vented condition. A constant loading rate of 0.005 %/min was performed in all cases. The void ratio, \( e_0 \), and the degree of saturation, \( S_3 \), at different test stages are given in Table 5.

![Fig. 5. Loading paths in water retention tests.](image)

![Fig. 6. Stress paths of unsaturated triaxial tests.](image)
Table 4. Void ratio and degree of saturation at different test stage in unsaturated triaxial test.

| Case | Right after preparation ($\varepsilon_0 = 1$) | Before compression | End of test |
|------|---------------------------------------------|-------------------|-------------|
|      | $e_0$ | $\varepsilon_0$ | $S_r$ | $e_0$ | $\varepsilon_0$ | $S_r$ |
| $s = 10$ | $p_{net} = 50$ | 0.73 | 0.64 | 0.78 | 0.68 | 0.73 |
| $s = 10$ | $p_{net} = 100$ | 0.78 | 0.60 | 0.66 | 0.64 | 0.62 |
| $s = 20$ | $p_{net} = 50$ | 0.82 | 0.67 | 0.43 | 0.72 | 0.40 |
| $s = 20$ | $p_{net} = 100$ | 0.77 | 0.61 | 0.35 | 0.68 | 0.32 |

5 TEST RESULTS

5.1 Saturated triaxial compression test

Fig. 7, Fig. 8, Fig. 9 and Fig. 10 show the test results of the large-scale saturated triaxial compression on sand, well-graded, gap-graded and coarse materials under undrained condition, respectively. The strength of the same material increased with the increase of confining stress. Strength of well-graded and gap-graded materials converted from increase to decrease along with the increase of axial strain, $\varepsilon_a$. It can be concluded that specimens of same material arrived at the same critical state line and the shear stress ratio at critical state was identical in spite of the specimen size. However, some of the test results, such as the test results of gap-graded material in Fig. 9, show that the specimens did not reach the static flowing state due to the limited axial strain. The shear stress ratios at critical state, $M$, of different LDM are listed in Table 5. The shear stress ratio at critical state of coarse material is the largest among all the LDM and that of gap-graded material is the smallest.
Table 5. Shear stress ratio at critical state, \( M \), of different materials.

| Type of material | Shear stress ratio at critical state, \( M \) |
|------------------|------------------------------------------|
| Sand             | 1.638                                    |
| Well-graded      | 1.578                                    |
| Gap-graded       | 1.286                                    |
| Coarse           | 1.804                                    |

(a) \( q \sim \varepsilon_a \)
(b) \( u_w \sim \varepsilon_a \)
(c) \( q/p'' \sim \varepsilon_a \)
(d) \( q/p'' \sim \varepsilon_a \)

Fig. 10. Test results of coarse material in undrained large-scale triaxial compression.

5.2 Water retention test

Fig. 11(a) and Fig. 11(b) show the test results of the water retention test on well-graded and gap-graded materials, respectively. The residual degrees of saturation of well-graded material and gap-graded material are 0.09 and 0.1, respectively, which shows great difference compared to the water retention test results in a larger scale of the corresponding materials (Xiong et al., 2018). The main drying and wetting curves of well-graded material are closer to each other than that of gap-graded material, which indicates the moisture hysteresis is less notable. However, it can be observed from Fig. 11(b) that the hysteresis of scanning curve of gap-graded material is almost invisible.

5.3 Unsaturated triaxial compression test

Fig. 12 shows the test results of unsaturated triaxial compression on gap-graded materials under undrained/unvented condition. Excessive pore water pressure (EPWP), \( u_w \), and excessive pore air pressure (EPAP), \( u_a \), both increased at first and then decreased significantly with the increase of axial strain, \( \varepsilon_a \). The degree of saturation, \( S_r \), and suction, \( s \), decreased gradually with the increase of axial strain, \( \varepsilon_a \). However, the suction, \( s \), before shearing was a little larger than expected. The suction change in case \( s=10, p_{net}=50 \) experienced a vibration as shown in Fig. 12(d), which indicates that this case needs to be reproduced. Identical critical state line was achieved in all cases. The shear stress ratio at critical state, \( M \), is 1.643 in unsaturated compression tests, which differs from that in saturated large-scale triaxial compression tests (1.286). This phenomenon may be resulted from the difference in maximum particle size. The strength increased with the increase of suction, \( s \), and the increase of net mean stress, \( p_{net} \). What’s more, the volumetric strain converted from compression to dilation with the increase of axial strain, \( \varepsilon_a \), while its relation to the suction and confining stress needs to be further checked, nevertheless.

6 CONCLUSIONS

A series of element tests on LDM was conducted in this study, in order to clarify the hydro-mechanical behavior of LDM.

It can be concluded from the results of saturated triaxial test under undrained condition that the peak strength of the landslide dam material increases with increase of confining stress. Moreover, the shear stress ratio at critical state, \( M \), of gap-graded and coarse materials are the smallest and the largest, respectively. It can be inferred that landslide dams made of coarse materials could be the most stable under the water level raising in landslide lakes. What’s more, specimen with...
Fig. 12. Test results of unsaturated gap-graded material in all triaxial compression tests.

300 mm in diameter and 300 mm in height can be used in the large-scale triaxial test.

The results of water retention test on well-graded and gap-graded materials indicate that the residual degree of saturation is almost the same for two materials and has the value around 0.1, which differs from the corresponding residual degree of saturation in a larger scale test (Xiong et al., 2018). The moisture hysteresis of gap-graded material is more notable than that of well-graded material, which is in consistence with the test result by Xiong et al. (2018).

Test results of unsaturated triaxial compression tests under undrained/unvented condition illustrate that the strength increases with the increase of suction and mean net stress. The volumetric strain transforms from compression to dilation along with the increase of axial strain in all cases. The shear stress ratio at critical state, \( M \), is 1.643 in unsaturated tests, differing from that in large-scale saturated test (1.286), which may be caused by the removing of particles larger than 2 mm. Therefore, the strength decrease due to the suction change under seepage loading may be the ignition of failure of landslide dams with gap-graded materials.

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