Shear Behaviors of Saturated Loess in Naturally Drained Ring-Shear Tests

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Abstract. A series of ring-shear tests was conducted on saturated loess to investigate the effects of shear rates and normal stress levels on the shear behaviors. The test results revealed that the effect of shear rate on shear strength of loess is strongly dependent on the normal stress levels. The peak friction coefficient of the samples is positively dependent on the shear rate when relatively low normal stress was imposed, whereas shear rate do not significantly affect the peak or residual friction coefficient for samples under high normal stress levels. But on the contrary, the residual shear strength of samples with pre-exiting failure surface increase slightly with increased shear rate under high normal stress level while kept constant under low normal stress level. Excess pore pressure was estimated to have built up within the shear zone and then can lead to a reduction in the shear strength after failure occur and the degree of reduction in post-failure shear strength was evaluated by the brittleness index.

Keywords: shear behavior, loess slope, ring-shear test, localized liquefaction.

1 Introduction

The Chinese second west-east gas pipeline project, which starts from Xinjiang in the west and reaches Shanghai in the east, passes through the 279km long Loess Plateau where loess gullies and loess slopes are the most common landforms [1]. The slope disasters, such as landslides and debris flows occur frequently in loess regions due to changes in triggering factors such as rainfall [2], climate [3], earthquakes [4] or human activities. For instance, 7 large-scale loess landslides have been determined in the Luiliang Mountain where the gas pipeline crosses. Furthermore, the existence of failure-prone slopes along the pipeline is a potential threat to the gas pipeline. Therefore, a deep understanding of the shear behaviors of loess is important.

In the survey of the project, a steep loess slope with local failures has been determined. To clarify the potential failure forms of this slope, we took samples from the slope area and investigated their shear behaviors by means of ring shear tests.

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According to the field survey, infiltration condition of this slope is well, therefore, ring-shear tests were conducted in naturally drained condition to mimic the naturally drainage of loess slopes. These tests were performed at various normal stress levels and shear rates to examine possible effects on shear strength and localized liquefaction characteristics.

2 Materials and Test Program

2.1 Materials

Three samples from different parts of the selected slope were collected for physical properties and grain size distribution tests. Table 1 shows index properties of the samples. The physical properties listed in Table1 are obtained following the procedures of Chinese Soil Testing Specification (SL237-1999). The grain size distributions of three samples were almost the same and approximately consisted of 85% silt, 7% sand, and 8% clay fraction by weight, respectively. Note that particles with diameter greater than 3mm were removed from the loess samples due to the size limitation of the shear box.

Table 1. Physical properties of loess samples

Properties	Water content ω/%	Natural density γ/(g·cm-3)	Liquid limit W_L/%	Plastic limit W_P/%	Void ratio e
Value range	2.70~6.10	1.41~1.50	26.1~26.5	17.1~18.2	0.90~0.94

2.2 Test Program

The ring-shear test program involved 12 specimens is shown in Table 2.

Table 2. Ring-shear test program of loess samples

Shear rate mm/min	Normal stress level /kpa			Shearing method
	100	300	600	
0.1-1.0-5.0-10.0	RS_1	RS_5	RS_9	Reversal shearing
1.0	RS_2	RS_6	RS_10	Single stage shearing
5.0	RS_3	RS_7	RS_11	Single stage shearing
10.0	RS_4	RS_8	RS_12	Single stage shearing

All specimens were prepared and saturated using the same method as Wang, Sassa [5]. For specimen named RS_1(5,9), reversal shearing test was conducted, that is, after shearing test at the previous stage of shear rate, the specimen was consolidated to stable condition and then sheared again at the next stage of shear rate. Each consolidation duration is approximate 6 hours. For other specimens, shearing tests were conducted in corresponding conditions using single stage shearing [6]. All the specimens were sheared to steady state in which the shear residence kept constant [7]. Tests were terminated when the shear displacement exceeded approximate 1000mm, at which time the shear residences were still changing slightly with progress of shearing for some specimens.

3 Results

The test results are summarized in Table 3. The variation of shear stress and sample height reduction with shear displacement at the shear rate of 0.1mm/min is shown in Figure 1, which is taken as a typical example to illustrate the test results.

Table 3. Summary of drained ring-shear tests

Specimen number	Shearing condition		Shearing state value				
	Shear rate	Normal stress	τ_p	τ_m	τ_r	L_d	H_d
RS_1	0.1-10.0	100	77.5	62.77	71.5	2127	0.52
RS_2	1	100	70.3	56.8	62.6	606	0.59
RS_3	5	100	77.5	57.9	62.7	837	0.74
RS_4	10	100	91.3	59.1	64.6	1318	0.59
RS_5	0.1-10.0	300	194.8	177.5	178.3	3200	0.74
RS_6	1	300	180.4	164.6	177	885	1.36
RS_7	5	300	192.4	169.6	185.9	887	1.23
RS_8	10	300	181.2	165.7	189.9	1165	1.35
RS_9	0.1-10.0	600	373.8	332.1	348.4	2500	0.8
RS_10	1	600	383.9	348.8	378.9	670	1.94
RS_11	5	600	385.8	354.5	355.5	976	1.52
RS_12	10	600	358.7	325.1	366.1	1001	1.94

Note: τ_p =drained peak shear strength; τ_m =the minimum shear strength after failure; τ_r =residual strength; and L_d , H_d = shear displacement and height reduction of specimen when the shear was stopped, respectively; Stress unit: kPa. Speed unit: mm/min Length unit: mm; For specimen of RS_1/5/9, reversal shearing were conducted using different shear rates, which are 0.1mm/min, 1.0mm/min, 5.0mm/min and 10.0mm/min, respectively, and shearing state values of specimen RS_1/5/9 in this table are the values after the first time of shearing.

As shown in Fig.1, after the shear stress, taking specimen RS_9 for example, was increased to peak (point A, 373.8kPa), shear failure occurred. The post failure process is consisted of two parts, a strain softening phase of fast decrease in shear stress and a strain-hardening phase of gentle increase in shear stress [5], that is, the shear strength of specimen suffered a certain amount of reduction after the shear failure occured and attained the lowest value (point B,332.1kPa), and then rose slowly to the steady state (point C, 348.4kPa). The other specimens have shown the same characteristic but with some differences. Usually, specimens under higher normal stress underwent much more amount of reduction and recovery in shear strength after failure. That means the post-failure process curve from point B to point C changed dramatically when high normal stresses were imposed and changed gently under relatively low normal stress levels.

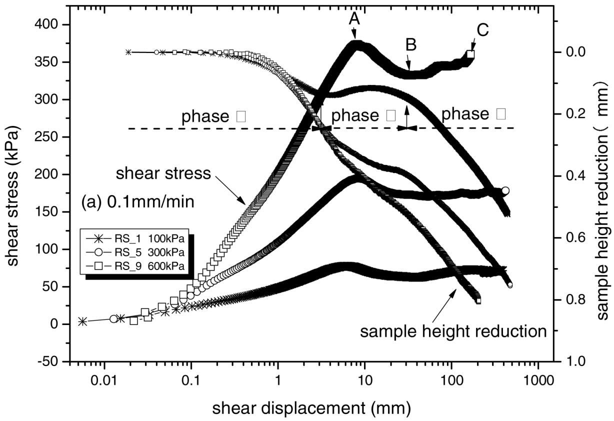

Fig. 1. Shear displacement vs. shear stress and sample height reduction at 0.1mm/min shear rate

The sample height reduction, to some extent, reflected the grain crushing properties in samples. During the entire shearing process, vertical displacement continue to increase. As shown in Fig.1, the height reduction in specimen RS_1 underwent three phases during shearing. According to the study of Wang, Sassa [8], the three phases can be defined as (I) initial negative dilatancy phase, (II) initial positive dilatancy phase (III) negative dilatancy phase due to grain migration, respectively.The positive dilatancy in the second phase was only observed in sample RS_1 which was sheared under the lowest normal stress level.

4 Discussion

4.1 Peak and Residual Shear Strength

The two naturally drained shear strengths considered herein are the peak and residual shear strengths [9]. Fig.2 shows plots of the variation of stress ratio τ/σ' with shear rate under various normal stress levels. It reveals that the peak friction coefficient (τ_p/σ') is relatively greater when the normal stress level is lower, and the peak friction coefficients (τ_p/σ') remain almost invariant for specimens under 300kPa and 600kPa normal stress levels. The peak friction coefficients appear to increase with increasing shear rate when normal stress level is 100kPa, while declined slightly under higher normal stresses [see Fig.2 (a)].

The relation between residual friction coefficient (τ_r/σ') and shear rate at different normal stress levels is shown in Fig.2 (b). As shown in this figure, the curves have slight changes with shear rate of 0.1mm/min, while remain almost flat with increased shear rate. It indicates that the shear rate and normal stress level have not significant effect on the residual friction coefficient (τ_r/σ'). This suggests that the peak failure envelope exhibits a larger stress and shear rate dependency than the residual failure envelope. This is probably because the normal stress and shear rate are the only factors that affect initial particle crushing and orientation in shear zone, whereas shear displacement prodominantly affects the particle orientation in the residual strength condition.

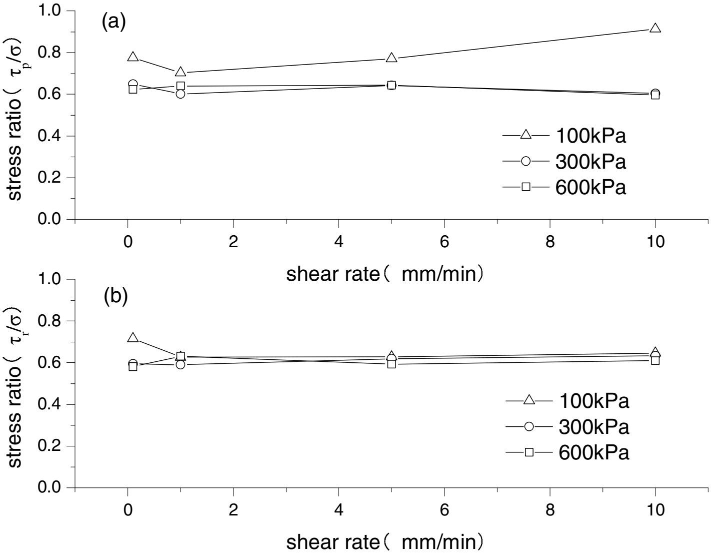

Fig. 2. The variation of stress ratio $\tau_{p(r)}/\sigma'$ with shear rate

4.2 Reversal Shearing Behavior

The reversal shearing test was performed to investigate the shear behaviors of loess sample with a pre-exiting shear surface that has attained a residual strength condition. The results are shown in Fig.3.

The stress-strain curves display different characteristics for samples under different normal stress levels in the reversal shearing process. The residual strength remained almost constant under normal stresses of 100kPa and 300kPa, whereas it appeared a fluctuant rising trend with increased shear rate under normal stress of 600kPa. It demonstrates that shear rate do not significantly affect residual strength when the normal stress is relatively low.

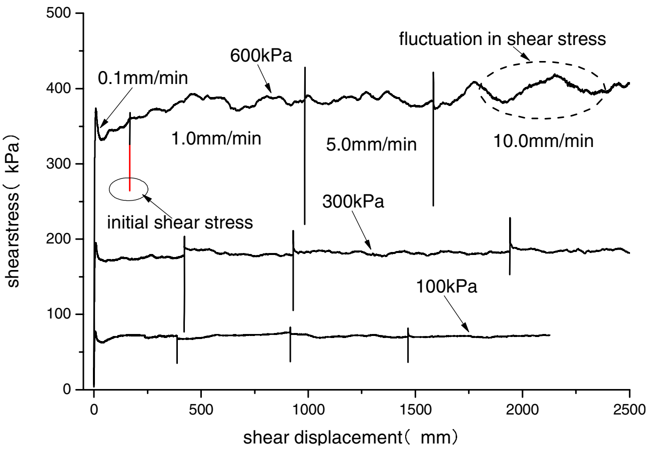

Fig. 3. Relation of shear displacement vs. shear stress for reversal ring shear tests

In the reversal shearing tests, loess samples had undergone previous shearing to generate a continuous shear surface and then consolidated to a stable condition. When restarted shearing at a greater shear rate, the shear stress rose perpendicularly from an initial shear stress to peak value which is larger than the peak strength gained in the previous shearing, and then drop to steady state, which referred to a residual strength condition (see Fig.3). It demonstrates that the shear surface in loess sample had undergone a healing process in the duration of consolidation, but the strength gained due to healing appeared to be lost after very small shear displacement, this is in accordance with the research of Stark, Choi [8], who studied the healing of shear surface on Duck Creek shale in ring shear apparatus with a long duration of consolidation. The mechanism of healing is not fully understood, and it is important to note that no significant generation of bond in the consolidation process due to the less content of clay fraction in loess samples.

4.3 Localized Liquefaction

The concept of localized liquefaction was first proposed by Sassa [10] in the undrained cyclic loading ring shear test. Localized liquefaction is induced by the shrinkage of soil volume due to crushing of grains with a consequence of the generation of excess pore-water pressure in the shear zone and reduction of shear residence. It is commonly realized that liquefaction failure is mainly caused by cyclic or static undrained loading, however, occurrences of many long run-out landslides have been reported for which no significant source of cyclic loading has ever been identified [11]. In fact, for soils in a natural slope, loading was applied in such a short time that the generated pore-water pressure could not dissipated immediately, and the generation of excess pore-water pressure is inevitable. Thus, generation and dissipation of pore-water pressure occurred simultaneously in the shear zone [5].

Bishop [12] expressed the reduction in undrained strength of a strain-softening material in terms of a brittleness index, which can be used to evaluate the magnitude of the strength loss and show relate post-failure behavior of a sample. The brittleness index I_B is defined as follows:

$$I_B = (\tau_p - \tau_m) / \tau_p$$

in which τ_p = peak shear strength; and τ_m = minimum shear strength after failure. The occurrence of localized liquefaction results in a reduction of shear strength in soil that may be large or small. Therefore, brittleness index could be adopted as a form of index in liquefaction analysis. A large brittleness index indicates a large reduction in shear strength that could lead to the progressive development of deformation after initiation liquefaction. On the contrary, the initial liquefaction in a material with a low brittleness index may not lead to significant deformations [11].

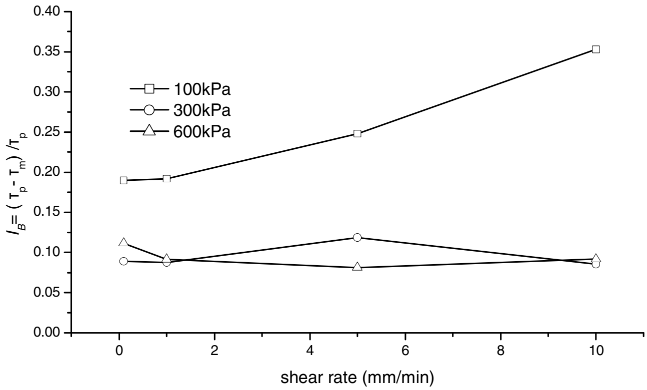

Fig. 4. Brittleness index against shear rate for different normal stress levels

As can be observed in Fig.1, each sample in this naturally drained shearing tests suffered a certain amount of reduction in shear strength after failure occur, and this reduction differed in various test conditions. To analyze the relative value between the peak shear strength and minimum shear strength after failure, the brittleness index against shear rate for various normal stress levels is presented in Fig.4. In all range of shear rate tests, the brittleness index for specimens under normal stress of 100kPa increased with increasing of shear rate. However, the brittleness indexes for specimens under normal stress of 300kPa and 600kPa are located in approximately the same level without an obvious tendency of change with the change of shear rate, probably due to the low initial void ratio. In addition, it can be noted that the cases of specimens under normal stress of 300kPa exhibit a convex and a concave pattern at shear rate of 1.0mm/min and 5.0mm/min, respectively. On the other hand, normal stress level has a negative effect on the brittleness index. This suggests that shallow loess slopes are more likely to suffer a large amount of deformation after initiation liquefaction. It is noted that this kind of localized liquefaction phenomenon has also been identified along the failure surfaces of some landslides triggered by earthquakes or heavy rainfall [13].

5 Conclusion

A series of ring-shear tests was performed on saturated loess taken from a loess slope. The shear behaviors of these loess samples was investigated by shearing them at different normal stress and shear rates in naturally drained condition. Conclusions were drawn as follow.

1. In the single stage shearing tests, the effect of shear rate on friction coefficient of loess is strongly dependent on the normal stress level. The peak friction coefficient of samples under low normal stress levels increase with increase of shear rate, while the shear rate do not significant affeted the peak or residual friction coefficient when relatively high normal stress was imposed.
2. In the reversal shearing tests, the residual shear strength for samples with pre-exiting failure surface increase slightly with increased shear rate under high normal stress levels while kept constant under low normal stress levels. In addition, shear residence on the shear surface in loess specimens had undergone a healing after the consolidation, but the grained strength due to healing appears to be lost after very small shear displacement.
3. Excess pore pressure was estimated to have built up within the shear zone and then can lead to a reduction in the shear strength after failure occured.The reduction of shear strength in post-failure process was evaluated by the brittleness index. The brittleness index increase with the increase of shear rate under relatively low normal stress level while keep constant under high normal stress level.

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