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Effect of Shear Rate on the Residual Strength of Clayey Soils

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Abstract: - The residual strength of soils in the shear zones at different shear rates can correspond to the movement of landslides. However, the rate-dependency of residual strength has not been quantified. A laboratory study on the residual strength of clay soils at shear velocities is present in this paper. The samples were extracted from the shear zone of a deep-seated landslide experiencing reactivation movement. The residual strength of samples at step-up shear rates from 0.5mm/min to 10000mm/min was obtained. Test results indicate that the samples at increasing shear rate tend to exhibit positive rate effect. At 10000mm/min the residual strength shows a gain of 2.21~2.68 times above the slow residual value. A model for predicting the residual strength correlating the shear rate is introduced. The different features in the slow and fast residual strength are attributed to soil fabric modifications within the shear zones. This is of practical significance to the stability and kinematic analysis of landslides.

Keywords: residual strength, rate-effect, normal stresses

I. INTRODUCTION

The determination of residual strength of soils is of vital importance when referring to many ancient landslips that contain pre-existing shear surface, because soils are at or close to residual condition and might exert a controlling effect on their possible reactivation. Huge amount of literature has accumulated since then associating with the risk assessment of ancient landslides at post-failure stage by use of drained or undrained residual strength parameters [1]. However, the effects of normal stresses and shear velocities on the residual strength remain unclear. This study aims to present an investigation into drained residual strength of soil samples at different conditions.

Designing of the ring shear device facilitates the measurement of residual strength, because it allows unlimited displacements and constant area of the shear plane as tests proceed. Since the 1930s, various experiment techniques were adopted in order to obtain drained or undrained residual strength parameters, among which the most well-known and extensively used would be the ring shear apparatuses designed by Bishop and. Bromhead. The series of DPRI ring shear devices developed by Sassa [2–4] are worth mentioning for their capability of applying seismic loadings and high velocity of shearing. This makes a contribution to understanding the rapid landslide movement. In early stages the ring shear apparatus was used to perform the stress-strain curves after peak strength with respect to some slow clayey landslides. Now the scope for it has been extended to exploring the triggering factors and the mechanism of landslide mobility.

Previous research has investigated the influence of shear rate on the residual strength of various soil samples. In early period the residual strength was normally obtained at relatively low rates of displacement, but then it was found to differ in fast ranges. Researchers [5–9] have made efforts to investigate the rate effect and its mechanism. It was revealed that the residual strength of many types of soils were rate-dependent, specifically displaying an increase, a decrease or no change in strength after a residual state was reached then sheared at a faster rate (Fig. 1). Three types of rate effect of residual strength were observed to have association with soil index properties (clay fraction and plasticity index) and the

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magnitude of normal stress [6,10–13]. A multistage ring shear test at normal stresses of up to 980kPa was conducted by Tika and Hutchinson (1999) to determine the residual strength of samples from Vaiont landslide. It was found a loss in strength of 60% occurred when the sample was at fast shearing. In some previous studies clay-rich soils appeared to show positive effect when shear rate was above a critical [10,14]. This compares well with results from Lemos[5], that soils rich in clay particles shear in sliding mode and tend to have positive effect. The mechanism of rate effect was partly attributed to the transition in shearing mode [15–19].

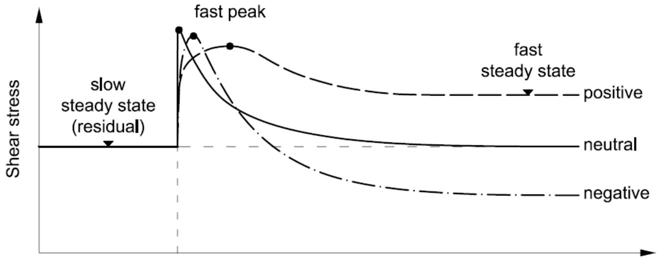


Fig. 1 Rate effect [1,5,20].

II. TEST APPARATUS AND MATERIALS

The ring shear apparatus in this study is designed following Bishop's configuration, that an annular ring-shaped specimen, subjected to a normal pressure and confined laterally, is ultimately caused to rupture by the relative rotation of the lower plate with the upper part fixed.

The shear box has inner and outer diameters of 13cm and 20cm respectively, and the thickness of samples is 6cm. It can load normal stresses of up to 3MPa and shear rate of up to 1m/s. Diagrams of Fig. 2 show a general view and the structure of this ring shear apparatus in detail.

During tests the shear resistance produced by rotation of the lower plate is transited by a torque arm and measured by a pair of load cells mounted on rigid columns. Normal stress is applied by the main shaft acting force on the loading platen. To maintain undrained condition and avoid possible leakage of soils or water during tests, a contact pressure is applied greater than the generated pore pressure controlled by a lift adjusting the gap distance of the upper and lower plates. Rubber edges in O shape are installed on the contact between upper and lower rings filled with silicon grease to ensure sealing. Teflon was sprayed on the rubber edge to reduce the effect of friction between the contact surfaces. Porous metal plates are placed at both loading platen and lower shear box allowing water to enter or exit, and transducers mounted on the upper ring can measure pore pressure changes near the shear zone. Vertical displacement of the specimen can be recorded by dial gauges to present changes in volume.

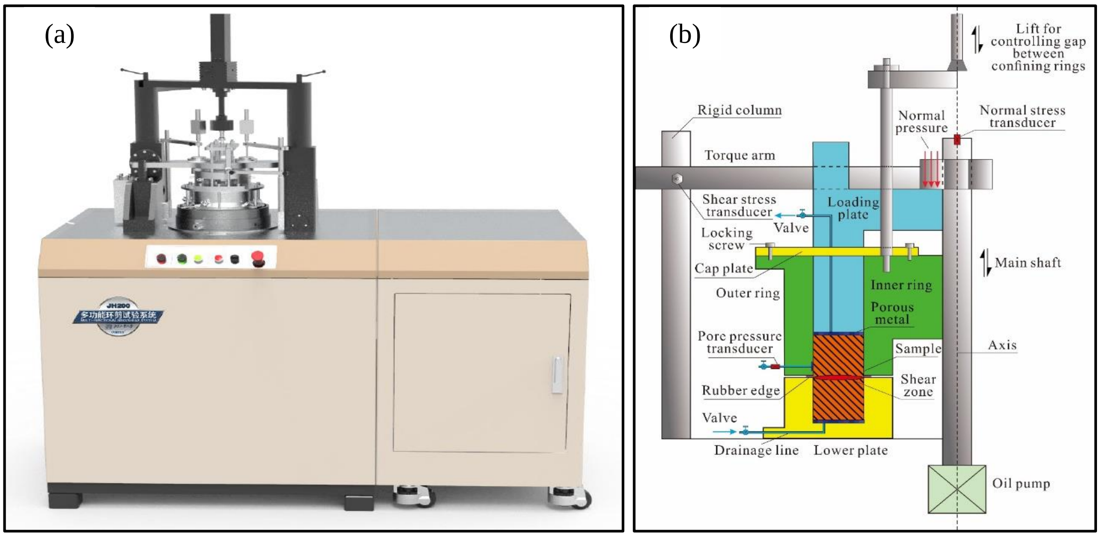


Fig. 2 Ring shear apparatus: (a) general view; (b) mechanical structure for the shear device.

Clayey soils taken from the shear zone of a deep-seated landslide are selected as the research objects. Physical properties including particle size distribution and plasticity index are given in Fig. 3 and Table1. The sample has clay fraction of 59% and plasticity index of 20.55, which can be defined as clay with low plasticity (CL).

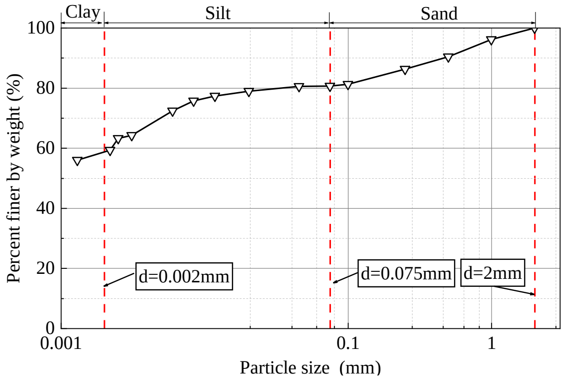


Fig. 3 Particle size distribution

Table 1. Physical properties of specimens

Gravity	Liquid limit (%)	Plasticity index	Clay fraction (%)	Silt fraction (%)	Sand fraction (%)
2.80	35.11	20.55	59	21	20

III. METHODOLOGY

There are three basic phases in a ring shear test including sample preparation, saturation and consolidation, which are briefly described as follows.

These samples were sufficiently segregated and sieved, then oven-dried at 105 °C for 24 h to fully remove water content. Soils were then placed into the shear box using a funnel in a free-fall deposition method described by Okada[21], and compacted layer by layer. After assembling the ring shear apparatus specimens were saturated by inletting de-aired water.

T1 was conducted to plot the residual strength envelope at a wide range of stresses. At each stage specimen was consolidated until the vertical displacement was less than 0.005mm/h, then sheared at a slow rate until a residual state was established to displacements of over 100mm. Once shearing had been completed it was subjected to the next stage of stress and consolidated. Speed-controlled tests (T1) were carried on specimens to enable the investigation of rate-dependency at varying levels of stress. Rate-stepped method was then adopted from slow to high velocity so that the rate dependency could be obtained. T2 was made to examine the difference in shear surfaces if the shear rate was changed. Note that the two samples at low and fast shearing in T2 experienced the same displacement. Test scheme is given in Table 2.

Table 2 Test scheme

Test number	Normal stress/kPa	Rate of displacement/mm·min^{-1}
T1	250	10-100-500-1000-5000-10000
	500	
T2	500	0.5
	500	1000

IV. RESULTS

Tests in speed-controlled mode are being made to measure the residual strength at fast shearing. The shear stress-displacement curves are plotted in Fig. 4. At the initial stage soils exhibit a slight strength-weakening at 10mm/min, then turning into a distinct gain in shear strength as the shear rate increases. The fast shearing of 10000mm/min gives rise to the slow residual strength from 69kPa to 185kPa (σ_n=250kPa), and 108kPa to 238kPa (σ_n=500kPa) respectively. The gain in strength tend to become pronounced at range of 100~500mm/min when some qualitative changes in behavior occur. Ratios of the residual coefficient of friction to the corresponding slow drained residual value, plotted against the rate of displacement, are shown in Fig. 5 (a), which indicates the positive correlation between residual friction and shear rates. As the rate of displacement increasing from 0.5 to 10000mm/min, the residual friction coefficient shows an increase of 2.68 times under 250kPa and 2.21 times under 500kPa. A model in the form of logarithm correlating the residual stress ratio and shear velocities is presented (Fig. 5 (b)), which is expressed by:

$$\mu_r = A \ln \frac{v}{v_c} + b \tag{1}$$

Where the μ_r is the residual friction coefficient (τ_r/σ_n'). v is the shear rate. v_c is the critical rate below which little or no disturbance occurs in shear zone, and the critical rate is defined as 100mm/min. A and b are parameters. The relationships between the residual friction coefficient and the shear rate are listed in Table 3.

The well-polished and smooth surface at 0.5mm/min, indicates the samples exhibit a typical sliding shear mode after long-distance shearing. Images of SEM (scanning of electronic microscope) in Fig. 6 show clear slickensides and striates along the direction of shearing, which demonstrates the alignment of clay particles. But the exposed shear surface at 1000mm/min is discontinuous and exhibits a fluctuating shape. This difference might be attributed to structural changes in the shear zones at varying shear velocities.

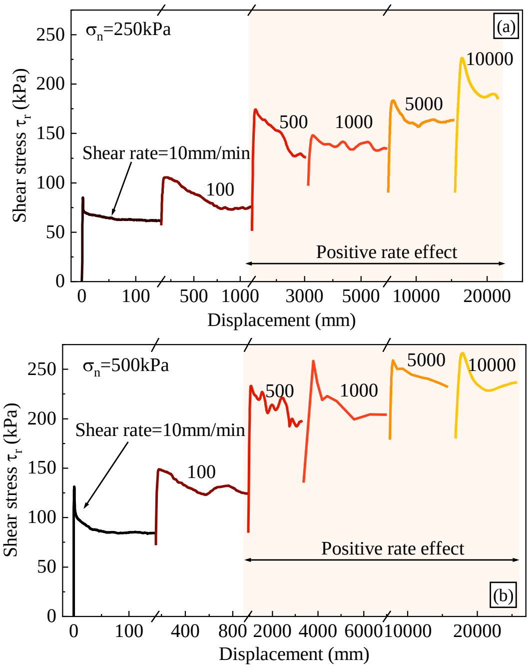
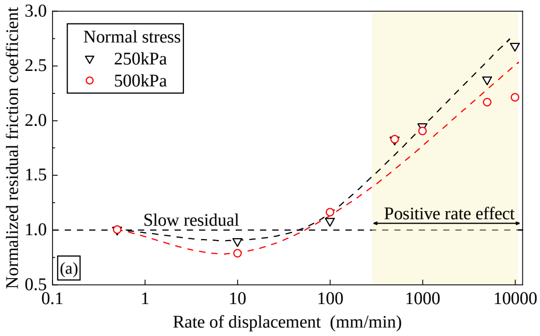


Fig. 4 Test results of T1: (a) shear stress at step-up shear rates, σ_n=250kPa; (b) shear stress at step-up shear rates, σ_n=500kPa



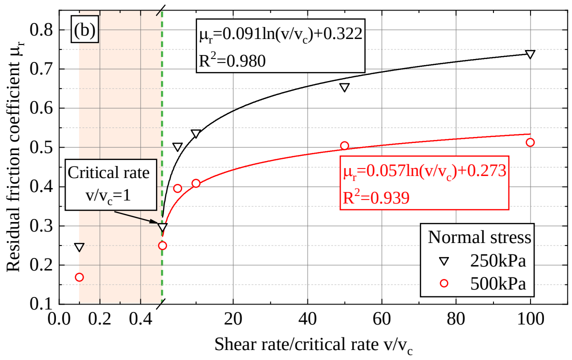


Fig. 5 (a) Normalized residual friction coefficient; (b) fitting curves correlating the residual friction coefficient and shear rate

Table 3 The relationship between the residual friction coefficient and the shear rate

Normal stress/kPa	The fitting relation	R^2
250	$\mu_r = 0.091 \ln \frac{v}{v_c} + 0.032$	0.980
500	$\mu_r = 0.057 \ln \frac{v}{v_c} + 0.273$	0.939

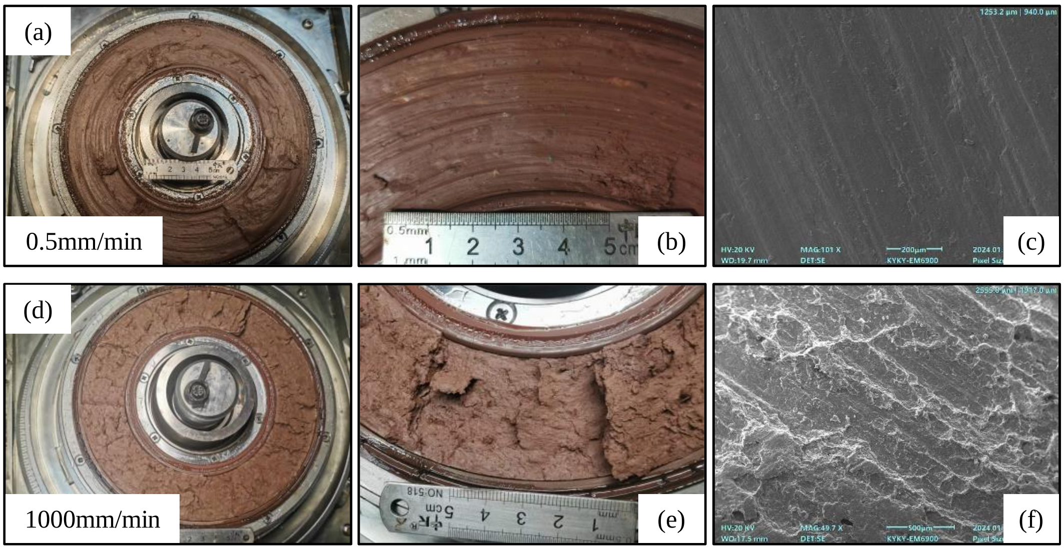


Fig. 6 Shear surfaces and SEM images at: (a)~(c) 0.5mm/min; (d)~(f) 1000mm/min

V. DISCUSSION

Fig. 5 (a) demonstrates the rate-dependency in terms of different normal stresses. The stress ratio-shear rate curve obtained at 250kPa lies above that at 500kPa, indicating that the critical rate tends to increase as the normal stress increases. Following Skempton[22] and Tika[6] the critical rate below which little or no disturbance occurs in shear zones varies at different normal stresses. This is possibly because the structure in the shear zone is less prior to change at higher normal stresses. Fig. 5 (b) shows that the residual friction coefficient at 250kPa is higher than that at 500kPa. The correlation between the residual friction coefficient and normal stress can be explained by the changes in the inter-particle friction. It has been reported the greater extent of particle orientation along the direction of shearing, with increasing effective normal stresses caused a reduction in the inter-particle friction coefficient. The plate-shaped particles tend to exhibit face to face interaction at high effective normal stresses[23,24].

It can be observed in this study that as the rate of displacement increases, the effect of rate strengthening becomes more pronounced, despite a slight decrease in strength during the initial stages at 10mm/min. Tika and some researchers identified this pattern of rate-dependency in silty clays and low plasticity clays. When the shear rate is changed there is a tendency towards volume decrease and the development of local positive excess pore water pressure. These locally existing pore water pressures may be responsible for the observed reduction in strength.

Previous studies have tried to explain mechanism behind the positive rate effect of clayey samples by the difference in shear surfaces, suggesting that the transition in shear mode is the mechanism of rate-strengthening in clayey samples. Similarly, in this study we infer that the soil samples exhibit a sliding shear mode at slow shearing, which can make a transition to a turbulent mode at fast shearing. This transition is reflected in the shear surface turning from a highly striated one, with the clay particles strongly orientated at slow shearing, to a disturbed and perturbated one at fast shearing, as proposed by Li[25], Miao and Wang[10]. The "turbulence" is not the involvement of round particles or high interparticle friction (>25°) within soils as defined by Tika[6], but the disturbance of the ordered structure in the shear zone. This receives support from the variations in the vertical displacement of soil mass at different shear velocities, as shown in Fig. 7. When the sample is tested at 0.5mm/min, a sliding mode mechanism is shown, characterized by a continuous settlement in the vertical displacement. High-speed shearing caused the structure to be disrupted, leading to an increase in shear resistance, specifically the turbulent shearing. This is manifested by the dilation at 5000mm/min and 10000mm/min. It can be inferred that the transition from sliding mode to turbulent might be the mechanism of positive rate effect.

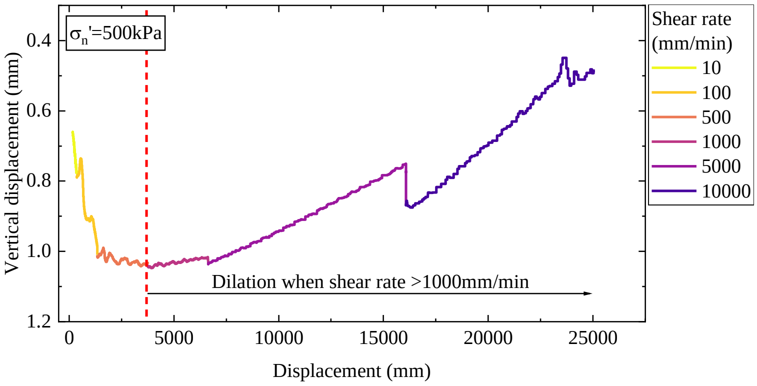


Fig. 7 Variation in the vertical displacement at step-up shear rates

Residual strength yielded under different rate of displacement in laboratory tests can correspond to extremely slow to rapid movement of landslides. Therefore in many studies rate effect has been used to predict landslide kinetics in reactivation. The weakening residual strength with increasing shear rate could promote the acceleration of landslide motion which might cause catastrophic rapture failure. If the sliding basal soil has positive effect, the "velocity-strengthening behavior" is able to resist the movement of sliding mass. This gain in strength when the sliding mass accelerates is likely to suppress high-velocity motion, and the strength will lose if it slows down [26]. The positive rate effect of soils in the shear zone, caused by the structural changes at fast shearing, might be the explanation of intermittent reactivation of some landslides.

VI. CONCLUSION

This study aims to present an investigation into the residual strength envelope at a wide range of stresses and the rate-dependency. Multistage ring shear test is conducted for varying effective normal stress and rates of displacement, in order to determine the residual envelope and the rate-dependency within a wide range of stresses.

(1) The clayey samples in the experiment exhibit a pronounced positive rate effect. The residual stress-rate relationship initially shows a slight decrease, followed by a significant increase. A model for predicting the residual friction correlating the velocities is introduced in the form of logarithm.

(2) The critical rate increases as the normal stress increases. Lower values of residual friction coefficient are shown when the normal stress is higher, for reasons that the degree of particle orientation is promoted at increasing normal stresses.

(3) The change in shear mode turning from sliding mode to turbulent mode, is the explanation for the

effect of rate-strengthening. This is supported by the changes in the structure of shear zones. The soil sample reveals a polished shear surface with slickensides at 0.1mm/min, but a discontinuous one with cracks at high rate of 1000mm/min.

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