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TECHNICAL PAPER

Shear rate effect on residual strength of typical clay soils

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Abstract

Residual strength parameters of clay soils along the slip surface of a slope are important parameters for stability analysis and countermeasure works against the activation and reactivation of landslides. The residual strength of slip surface soil is defined as the minimum constant value attained after a large displacement, which may equivalent to the measured residual strength of such slip clay soils in the ring shear test. However, the previous studies reported that the residual shear strength of clay soils may vary with shearing rates in ring shear tests. Therefore, further investigation is needed to understand the relation between the residual strength and shear rates for various types of clay soils collected from the reactivated landslide sites. Moreover, the effect of shear rate on the residual strength of high- to low-plasticity soils with the presence of different clay minerals has not yet been fully understood. The main objective of this study is to understand the rate dependency of the residual strength of typical clay soils from the soil plasticity and clay mineralogical perspective, and the shear rate effect mechanisms behind it. This paper presents the effect of shear rates on residual strength of various typical clay soils having high-to-low plasticity in its soil natures. The shear rates were fixed in a range of 0.073–0.586 mm/min at different six shear rates (i.e., 0.073 mm/min, 0.162 mm/min, 0.233 mm/min, 0.313 mm/min, 0.398 mm/min, and 0.586 mm/min). A series of tests were performed by means of torsional ring shear apparatus in the fully natural drained condition under an effective stress of 98.1 kN/m^2. Shear rates on residual strength of the high-plasticity soils, medium-plasticity soils, and low-plasticity soils having various clay minerals were compared. The results showed the neutral rate effect on the residual shear strength of typical clay soil at shear rates of 0.073 mm/min, 0.162 mm/min. Similarly, the positive rate effect on residual strength of typical clay soils was confirmed at shear rates of 0.233 mm/min, 0.313 mm/min, 0.398 mm/min, and 0.586 mm/min. The relation between residual friction coefficient and shear rate of typical clay soils was also presented. Finally, shear rate mechanism of clay soils was discussed based on the variation of residual friction angles with shearing rates.

Keywords Residual strength · Shear rate effect · Clay soils · Ring shear test · Stability analysis · Reactivated landslides

Introduction

For the stability analysis and design of countermeasure works against the reactivation of landslides, the effective shear strength parameters such as frictional angle (ϕ') and the cohesion (c') of slip clay soils are necessary. Moreover, the effective residual strength parameters (ϕ'_r, c'_r) could be also used for evaluating the stability and movement behavior of the first-time slide. The residual strength parameters of soils are the most important parameter in the stability analysis of ancient landslide and reactivation potential evaluation [3–6]. If there is a slight change in the residual strength parameters, the net results of the stability assessment of landslides might be also affected [8–10]. For example, if the applied stress of a sliding block is less than the residual strength of slip soil (i.e., factor of safety is greater than one), a slope cannot fail. When the residual strength may increase from its residual state, it could prevent catastrophic landslides because the increased in strength also increase in stability of slopes. Alternatively, when the residual strength of the slip surface soils decreases from its residual state in a short time, the slope may lead to fail due to decrease in stability of slopes. The accurate determination of residual shear strength parameters and their dependence on the shear rate may affect the stability evaluation of landslides [1, 2, 11, 33]. Moreover, if there is a possibility of change in measured residual strength with the variation of the shear rates for the

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same slip clay soil of a landslide, the effect of shear rates on residual strength should be carefully considered during the determination of the residual strength parameters to obtain design parameters with high accuracy and reliability. Therefore, the study of the shear rate effect on residual strength of slip clay soils is important in geotechnical engineering for estimating the accurate design strength parameters for stability analysis of slopes. Moreover, a better understanding of the shear rate effect on residual strength of slip clay soils and associated shear rate effect mechanisms would be beneficial in predicting and evaluating of the activated and reactivated landslides, and at the same time, long-term management of such landslide problems would be easy in future.

The reversal direct shear test and ring shear test are widely used to measure the residual strength of clay soil in the laboratory. In the reversal direct shear test, the soil specimen is sheared forward and backward direction with a minimum shear resistance (i.e., less than 0.5 cm). As a result, the specimen is not subjected to continuous shear deformation in one direction, and thus, a full orientation of the clay particles parallel to the direction of shear may not be obtained [33]. Therefore, the measured residual strength using the reversal direct shear test may not represent the true value of the soil strength in a practical sense [37]. However, recent research trends show that a ring shear apparatus is being widely used to measure the residual shear strength of a clay soils [4–6]. The main advantage of the ring shear apparatus is that it can shear the specimen continuously in one direction to obtain the large displacement, and this allows the clay particles to be oriented parallel to the direction of shear to develop the true residual shear strength condition [12, 21, 36]. Another advantage of the ring shear device is that no change occurs in the shear plane area during shear [37, 38]. For the precise measurement of residual strength, the large deformation is applied to a specimen so that clay particles are oriented along the shear surface in the direction of shear to the maximum possible extent [18, 29, 33]. Therefore, it is a generally accepted fact that the measured residual strength using the ring shear test allows the soil specimen to be sheared at ultimate displacement, which may simulate the field condition of reactivated landslide more accurately than other lab tests [4–6, 9, 10, 22, 33].

Lupini et al. [24] reported that the residual shear strength changes with clay content of the cohesive soil in ring shear test. The effect of shear rate between 0.002 and 0.1 mm/min on residual strength was negligible in clay soils [33]. Lemos et al. [23] reported that the residual shear strength of soils with high clay content increases and decreases with a low clay content. Yatabe et al. [42] reported that the residual strength of clays in fractured-zone landslide areas hardly increases with the increase in the shear rates. Yokota et al. [43] concluded that the shear rates below 1.01 mm/min do not affect the residual shear strength in ring shear tests. Tika et al. [35] stated that some soils show greater shear strength than the residual strength (i.e., positive rate effect) in high shear rates, while some soils exhibit a lower strength (i.e., negative rate effect) or a constant shear strength (neutral rate effect) with varying shear rates. Suzuki et al. [34] reported that the shear rate in a range of 0.02–2.0 mm/min significantly influenced the residual strength of clay soils and mud stone. Bhat et al. [1, 2, 7] and [11] reported the hardly increase in the strength from the residual state of shear on kaolin clay and landslide soils in slow shear displacement rates. Scaringi and Maio [32] pointed out that the residual shear strength of kaolin and bentonite has increased with the increase in displacement rate. The shear-rate-dependent behavior of clayey biomaterial interfaces in a range of shear rate of 0.002–120 mm/min under normal stress of 150–1500 kPa was discussed by Scaringi et al. [30]. Scaringi et al. [31] discussed the various rate effect behaviors (i.e., neutral, positive, negative rate effect) of soil based on the presence of clay minerals. The shear rate effects on dry and saturated mudstone gravels with different gain sizes in a wide range of displacement rates (0.005–100 mm/s) were reported [19]. Similarly, Hu et al. [17] stated the suction and rate-dependent behavior of a shear-zone soil from a Kualiangzi landslide in the Sichuan basin of China. Slow shearing rate effects on residual strength of landslide soils (which included high- and low-plasticity soils as well as clay-rich and silt-/sand-rich soil types) have been studied by Kimura et al. [20] using ring shear test. Kimura et al. [20] concluded the negative shearing rate effect on residual strength at low effective normal stress. Gratchev and Sassa [15] indicated that there is an immediate increase in residual strength pre-sheared clays from its residual state (i.e., positive rate effect) when the shear rate is also increased in ring shear test [15]. The rate and acceleration effects on residual strength of high-plasticity soil using the ring shear test have been discussed by Duong et al. [13] and concluded that the shear rate effect on residual strength of high-plasticity soil cannot be neglected; however, the effect of acceleration can be neglected in determining the residual strength. Wang and Cong [39] discussed the role of water content and shearing rate change in the residual shear stress of slip soils using the ring shear test results. Lian et al. [22] reported the shear rate effect on the residual strength characteristics of saturated loess in naturally drained ring shear tests at two shear rates (i.e., 0.1 and 1 mm/min) and revealed that the residual shear parameters reduced with the increase in the shear rate in the loess area. Wang et al. [40] investigated the variation in shearing rate effect on residual strength of slip zone soils using ring shear tests and concluded that the residual strength decreases with increasing shearing rate (i.e., negative rate effect) and exists a good linear relationship with the logarithmic shearing rates. Hu et al. [17] also concluded the possibility of the negative-rate effect behavior at low rates of shear displacement.

In summary, the previous studies have been recognized the three types of variation of the residual strength of clay soils with a variation of shear rates, which are named as positive rate effect [1, 2, 7, 11, 15, 22, 27], the neutral rate effect [15, 22, 23, 26, 33], and negative rate effect [15, 17, 20, 40]. In the positive shear rate effect, the residual shear strength increases with a variation of shear rates under a given normal stress. Similarly, when the residual shear strength does not change with a variation of shear rates under the same given normal stress, it is called neutral rate effect. On the other hand, if the residual shear strength of clay soil may decrease with a variation of shear rates, it is named as negative rate effect. The simple sketch of negative, positive, and neutral rate effects on the shear behavior of clay soils is shown in Fig. 1. Based on the above discussion, it can be concluded that the shear rate effects on the residual strength of various types of soils are not fully understood and need further investigations. This study confirms the positive and the neutral rate effect on the shear behavior of testing clay soil. The details are discussed in section "Results and Discussion" of "Shear behavior" section.

The basic understanding of the reactivated landslides is that it has already experienced very high shear deformations or displacements, and the slip surface's soil materials of such landslides have already reached a stable or steady state, which is called a residual state [3–6, 8–10]. However, the previous studies [1, 2, 7, 11, 15, 20, 22, 23, 26, 27, 33, 40] suggested that the residual shear strength of slip soils of reactivated landslides may vary (i.e., decrease, increase and neutral) with the variation of the shear rates after the large displacement in laboratory tests. However, the mechanism(s) behind such variation in strength from its residual state of shear of slip clay soils of reactivated landslide with change in shear rates are not yet fully understood. On the other hand, the shear rate effect on the residual strength of the clay soils having the different clay minerals such as kaolinite, smectite, chlorite, and illites has not been sufficiently investigated. To address the above-mentioned problems, the shear rate effects on the residual strength characteristics of different clay soils should be further investigated from both soil plasticity and clay mineralogical perspective. Therefore, the primary aim of this study is to understand the shear rate effect on residual strength of typical clay soils having high-to-low plasticity in their soil's nature and their possible shear rate effect mechanisms. The specific objectives of this study are: (i) to confirm the residual strength of clay soils either varies or not with the variation of the slow shear rate using the torsional ring shear test, (ii) to conduct a comparative study of shear rate effect on shear behavior of high-plasticity soils, medium-plasticity soils, and low-plasticity soils, (iii) to establish the relation between the residual friction coefficient and shear rate of typical clay soils, (iv) to understand the mechanism(s) behind the change in shear strength from the residual state of shear with variation of the shear rates in ring shear test. In this study, four typical clay soils having high plasticity to low plasticity in their soil's nature were tested with varying shear rates of 0.073–0.586 mm/min at six shear rates (i.e., 0.073 mm/min, 0.162 mm/min, 0.233 mm/min, 0.313 mm/min, 0.398 mm/min, and 0.586 mm/min) using the ring shear apparatus. The physical soil properties such as solid density, liquid limit, plastic limit, and plasticity index of selected typical clay soil have been examined and quantified the percentage of clay and silt and sand particles. In addition, the X-ray diffraction tests were also performed to confirm the presence of clay minerals on the tested samples. This paper primly describes the shear behavior, residual friction coefficient and shear rate relation, and shear rate effect mechanism based on the experimental results of the torsional ring shear test.

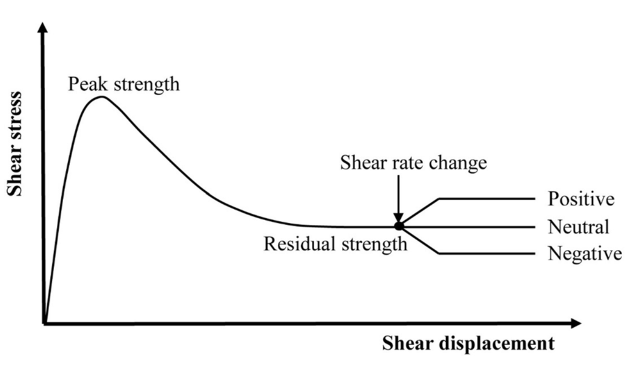


Fig. 1 The basic concept of negative, positive, and neutral rate effect on shear behavior

Materials and method

Selection and description of tested samples

In this study, four typical clay soils were taken. One sample was commercially available kaolin clay, named as "Clay soil-I", and other three clay soils were collected from the landslide sites in Japan and Nepal (Refer Bhat et al. [6] for details of sample collection of landslide area). The second tested sample was collected from the Krishnabhir landslide of Nepal. Figure 2 shows the typical X-ray diffraction patterns of the second clay soil. From the power method, the maximum value of the peak intensity was recorded at a diffractive angle between 9.9° and 10.1°, which represented the mica as the main constituent mineral. Moreover, the peak intensity (i.e., at 9.9° to 10.1°) for mica mineral was also confirmed by the sedimentation method and the ethylene glycol method (Fig. 2).Therefore, the selected

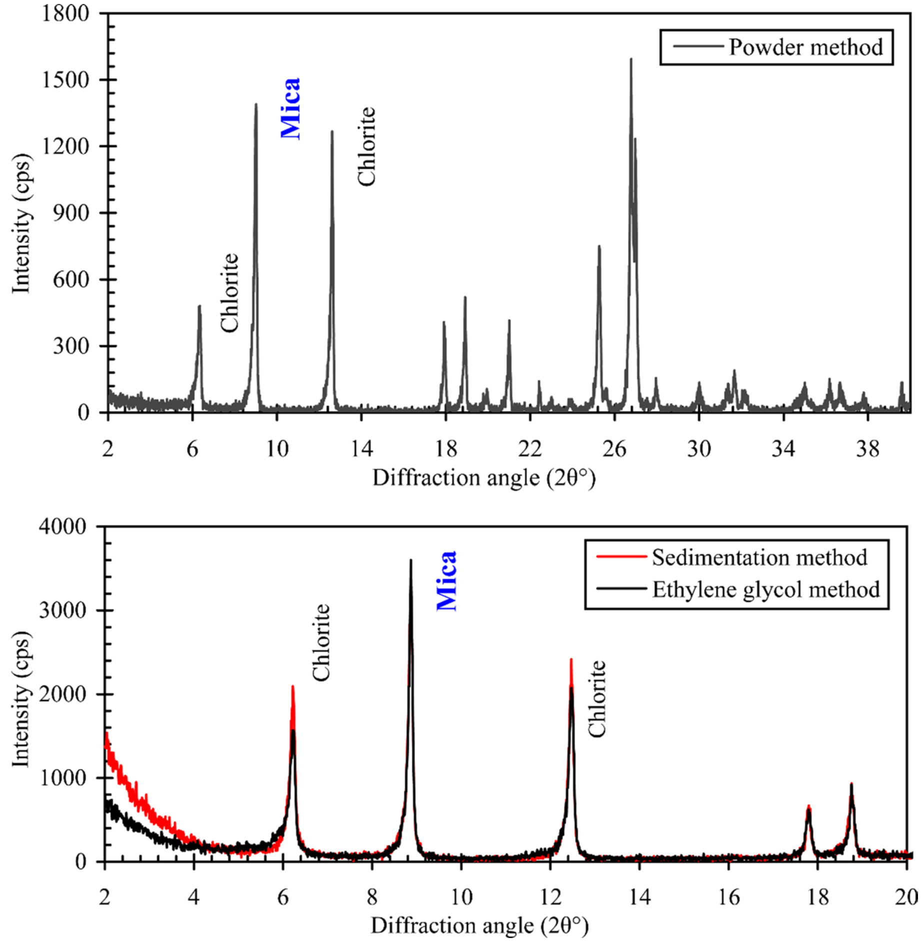


Fig. 2 A typical X-ray diffraction patterns of the Clay soil-II

second clay soil was confirmed to have a comparatively high amount of mica, which was referred to as "Clay soil-II". Similarly, the third clay soil was collected from the Shikoku landslide of Japan. Figure 3 shows the typical X-ray diffraction patterns of the third clay soil. From the power method, the maximum value of the peak intensity was recorded at a diffractive angle between 6.1° and 6.4°, which represented the chlorite as the main constituent mineral. The peak intensity (i.e., at 6.1° to 6.4°) was also confirmed by the sedimentation method and the ethylene glycol method as shown in Fig. 3. Hence, the third clay soil was confirmed to have a comparatively high amount of chlorite, which was referred to as "Clay soil-III." The fourth clay soil was collected from the Toyooka-kita landslide of Japan. The results of X-ray diffraction patterns of the fourth clay soil are presented in Fig. 4. In the power method, smectite mineral showed the maximum value of the peak intensity, which represented the smectite as the main constituent minerals. The obtained peak intensity from the power method was changed and the maximum peak intensity was observed at a diffractive angle between 5.2° and 5.5° in the case of the sedimentation method and the ethylene glycol method (Fig. 4). This means that the presence of smectite mineral was higher when compared to other minerals. Therefore, the fourth clay soil was confirmed to have a comparatively high amount of smectite, which was named to as "Clay soil-IV".

The plasticity index of the Clay soil-IV was the highest and followed by the Clay soil-I, the Clay soil-III, and then the Clay soil-II, respectively. The clay particle size (i.e., < 2 μm) of the Clay soil-I was also the highest and the lowest for the Clay soil-III (Table 1). The silt particles were highest on the Clay soil-III when compared to the other clay soils. Similarly, the presence of sand particles was confirmed maximum on the Clay soil-IV. The influence of particle size distribution on the residual shear strength of clay soils is studied by Yatabe et al. [42]. Yatabe et al. [42] have concluded that the residual shear strength of a soil sample is controlled by the matrix material when the content of the sand particles is less than 30%. Therefore, we have taken the particles passing through 425-μm sieve and assumed that the particles with diameter greater than 425 μm have a negligible effect on the residual shear strengths of the soil samples. The grain size distribution curves of the typical clay soils are shown in Fig. 5.

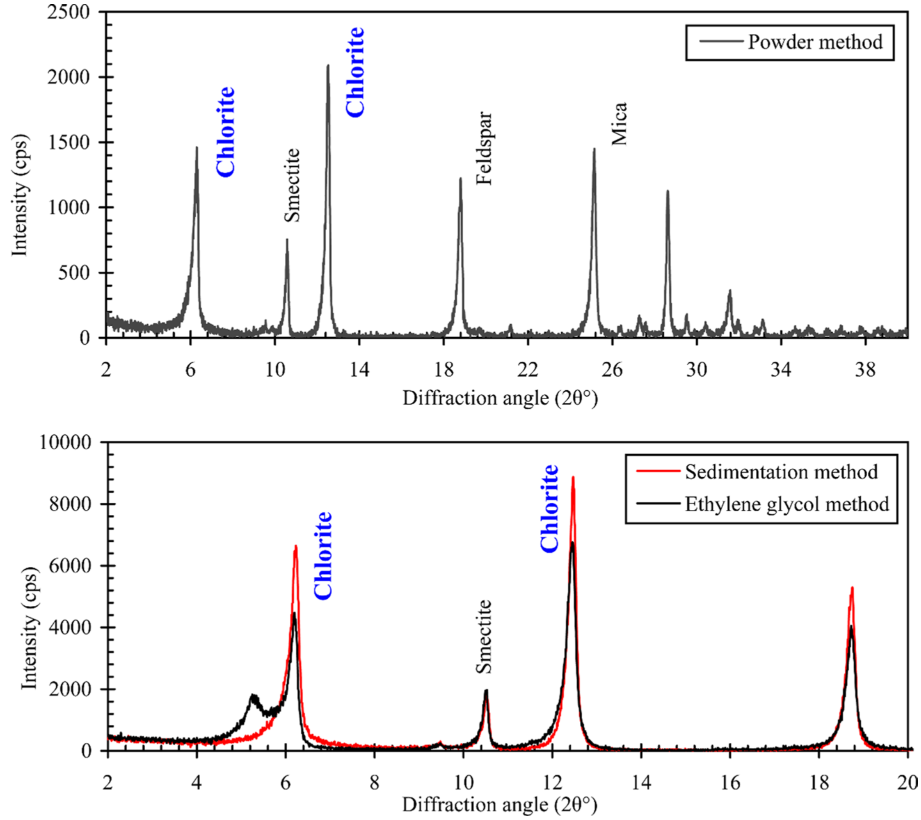


Fig. 3 A typical X-ray diffraction patterns of the Clay soil-III

Test procedure

In the ring shear apparatus, the lower half of the apparatus is below the plane of failure rotates, whereas the upper part is fixed. During operation, a resistance develops in the upper part, and the value is measured by a load cell, which measures the shear force due to the rotation of the lower part transmitted to the upper part through the sheared soil specimen. The ring shear apparatus (based on the concept reported by Bishop et al. [12]) was used in this study. In this ring shear apparatus, the specimen container has inner and outer diameters of approximately 8.0 cm and 12.0 cm, respectively, and an average thickness of 2 cm. The specimen is sheared through a level of 0.7 cm above the base of the lower plate. The ratio of the outer to inner ring diameters is 1.5. In this study, all tests are conducted in a naturally drained condition. The gap between the upper and lower confining rings of the apparatus is fixed at 0.2 mm to reduce/minimize the friction between the upper and lower confining rings and of the overflow of the specimen from the shear surface during shear. The size of the gap is maintained by means of three screws. Moreover, the grease was also used on the ‘O’ ring (rubber) to reduce the friction between the contact surface of ‘O’ ring (rubber) and test specimen during the shear test. The excess pore water pressure is assumed to dissipate and to have no influence on the normal stress in the fully drained natural condition. Thus, the effect of pore water pressure is negligible. Consequently, the total applied pressure works as effective pressure, and the entire test system is under an effective stress condition. The normal load is transmitted to the sample by the central shafts which can directly apply. Mechanisms are made in such a way that there is no eccentricity during the application of normal load and shear strain during the test. The details of cross section of the ring shear apparatus are shown in Fig. 6.

The ring shear test is conducted to determine the strength parameters at the residual state of shear of soils. There are three basic stages in the ring shear test: (a) sample/specimen preparation: first, sample/specimen preparation was carried out. For this, about 200 g of finer than 425-μm dry sample was mixed with distilled water until it turned into a thick liquid (i.e., viscous liquid). The fully mixed thick liquid sample was then de-aired in a vacuum chamber to make it fully saturated. The de-aired sample was then poured into a specimen mold and pre-consolidated under desired loads for about 24 h. Then, the specimen was carefully transferred from the specimen mold to the specimen container of the ring shear apparatus for further consolidation and shear. (b) Consolidation stage: Next, the specimen was consolidated further before shear was begun. In the consolidation stage, at first an effective normal stress of 196.2 kN/m^2 was applied, and after the end of the consolidation, the effective normal stress was reduced to 98.1 kN/m^2 to achieve an over-consolidation

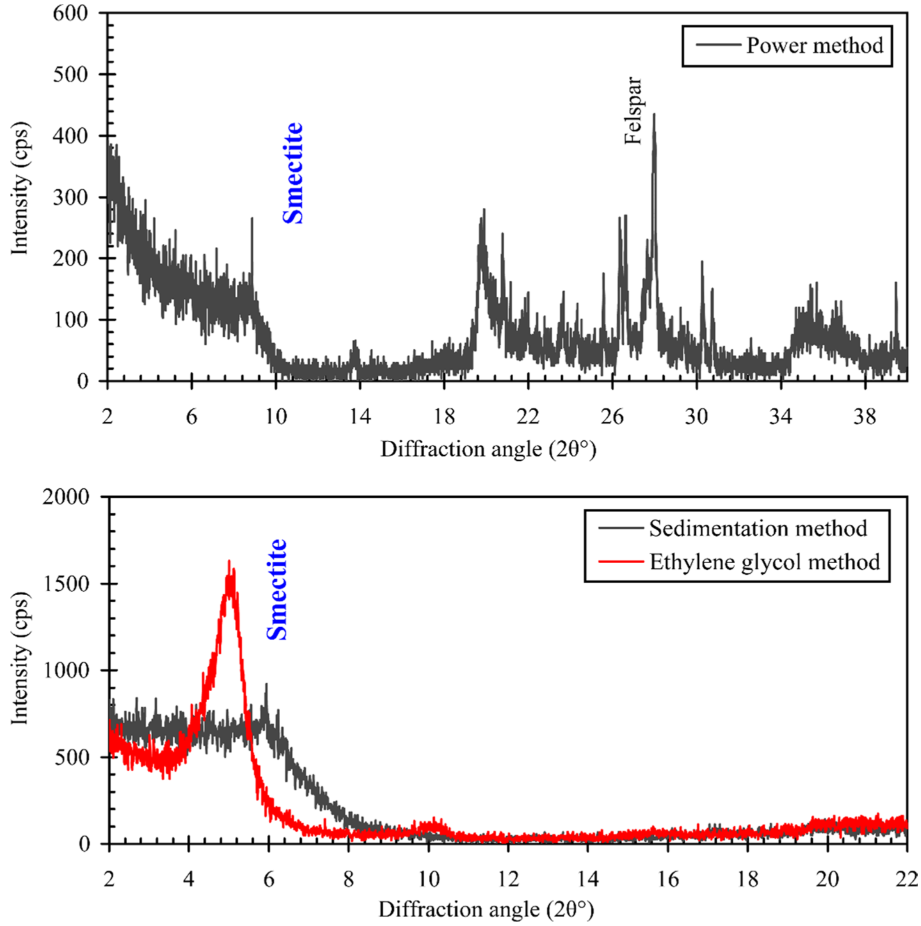


Fig. 4 A typical X-ray diffraction patterns of the Clay soil-IV

Table 1 Physical properties of the tested samples

Sample name	Solid density, G_s (g/cm^3)	Liquid limit, LL (%)	Plastic limit, PL (%)	Plasticity index, PI (%)	Soil classification		
					Clay (%)	Silt (%)	Sand (%)
Clay soil-I	2.72	52	22	30	74	26	0
Clay soil-II	2.74	34.1	20.7	13.4	21	59.7	19.3
Clay soil-III	2.75	47.5	31.2	16.3	20	68.1	11.9
Clay soil-IV	2.65	96.5	59.0	37.5	24	18.0	58.0

ratio (OCR) of 2. This was done for the purpose of obtaining a distinct difference in peak and residual strength because in most cases of normally consolidated clay samples in the ring shear apparatus, the amount of drop from the peak to residual strength is insignificant. So, all shear tests were conducted under an effective normal stress of 98.1 kN/m^2. (c) Finally, the over-consolidated specimens were sheared at different rates of shear. The shear rates were varied from 0.073 to 0.586 mm/min (i.e., 0.073 mm/min, 0.162 mm/min, 0.233 mm/min, 0.313 mm/min, 0.398 mm/min, and 0.586 mm/min) and the shear was continued until a specimen reached its residual state of shear. The overall flow of the experiment is shown in Fig. 7.

Results and discussion

The results of the various slow shear rates of the Clay soil-I, the Clay soil-II, the Clay soil-III, and the Clay soil-IV are presented in terms of variation of shear stress to shear displacement and the variation of volumetric strain with shear displacement in Figs. 8, 9, 10, and 11, respectively. The residual state of shear was confirmed about the 10 cm of shear displacement for all tested clay soils; however, continuous shearing was performed upon the shear displacement of 15 cm for the further confirmation of the residual strength of soil. It was confirmed that there was

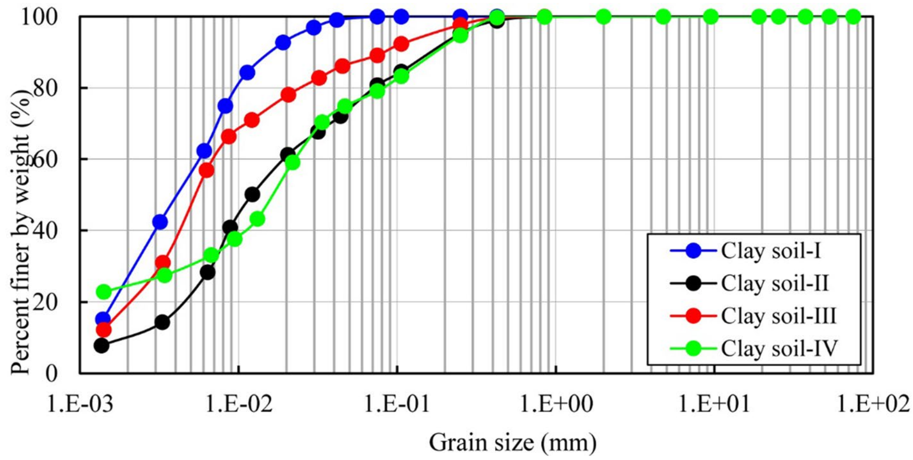


Fig. 5 Grain size distribution curves

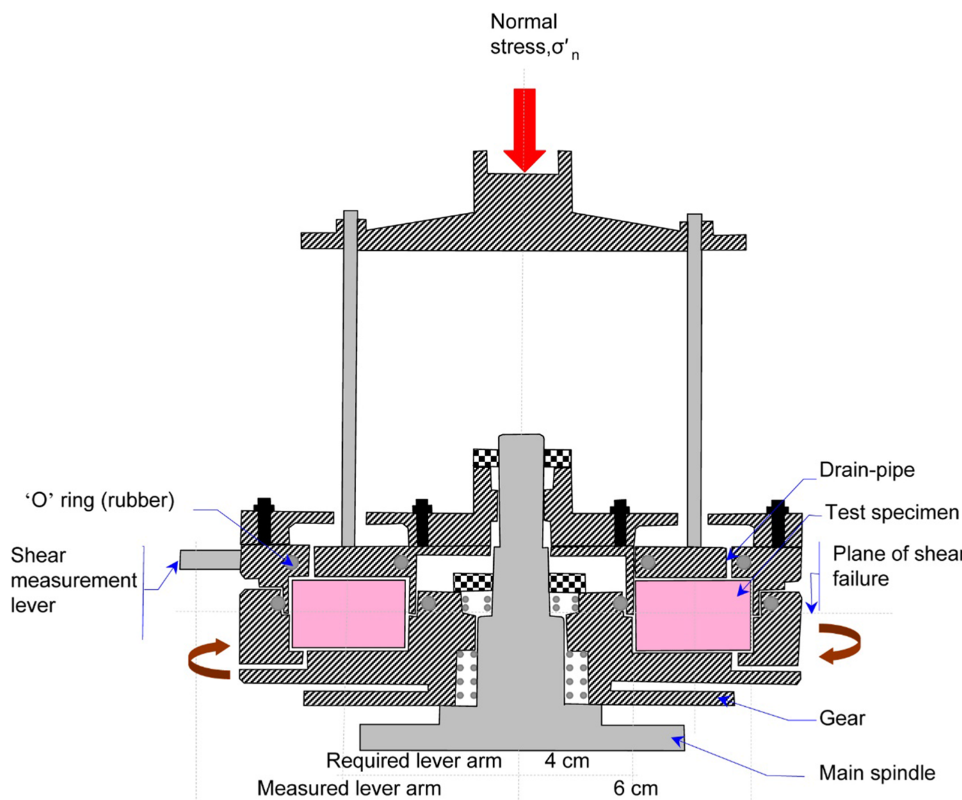


Fig. 6 Structural features of direct ring shear apparatus

not any change in residual state of shear after the shear displacement of 10 cm (Figs. 8, 9, 10, and 11). The ring shear test results indicated that the peak strength and the residual shear strength of the Clay soil-I were the highest and followed by the Clay soil-II, the Clay soil-III, and the Clay soil-IV (Figs. 8, 9, 10, and 11). For example, at the shear rate of 0.073 mm/min, the peak strength and the residual strength of the Clay soil-I were noted 53.45 kN/m^2 and 48.13 kN/m^2, respectively. Similarly, the peak strength and the residual strength of the Clay soil-II, the Clay soil-III, and the Clay soil-IV were recorded 51.10 kN/m^2 and 44.87 kN/m^2, 43.70 kN/m^2 and 24.88 kN/m^2, and then 40.55 kN/m^2 and 8.88 kN/m^2, respectively. In the case of the shear rates of 0.162 to 0.586 mm/min, the test results of the shear stress versus the shear displacement and the volumetric strain versus the shear displacement of the Clay soil-I followed the similar pattern as the results obtained at a shear rate of 0.073 mm/min (Fig. 8). Similarly, the similar patterns of the stress–strain curves were observed in the shear rate of 0.162 to 0.586 mm/min in the cases of the Clay soil-II, the Clay soil-III, and the Clay soil-IV, respectively (Figs. 9, 10, and 11). It was observed that

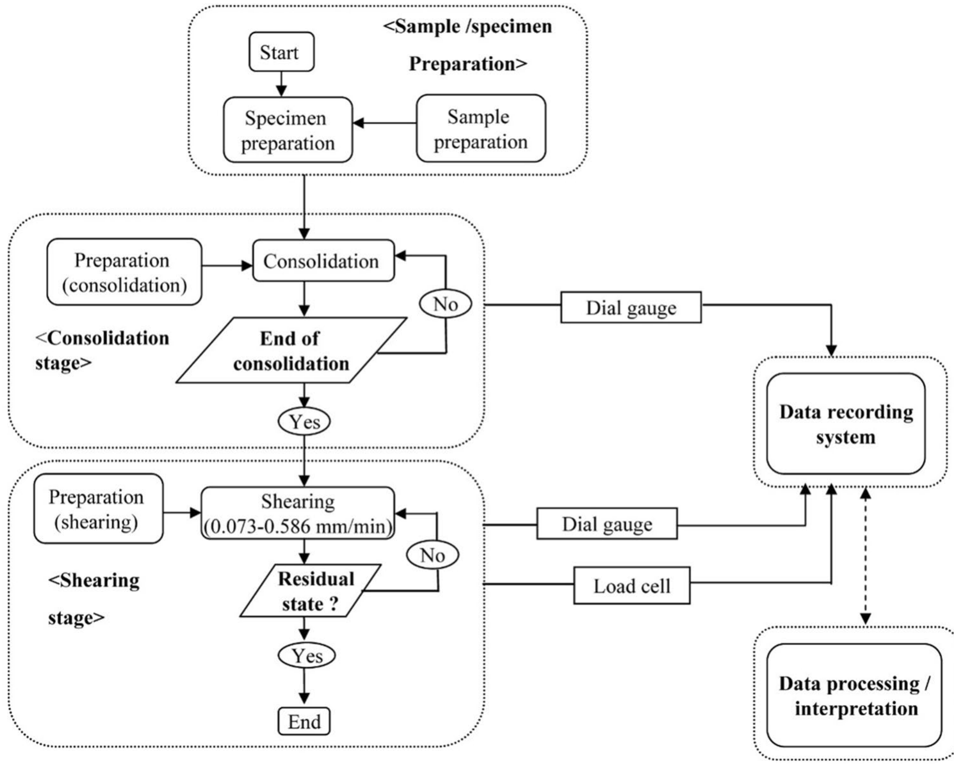


Fig. 7 Overall experimental flow of shear rate test

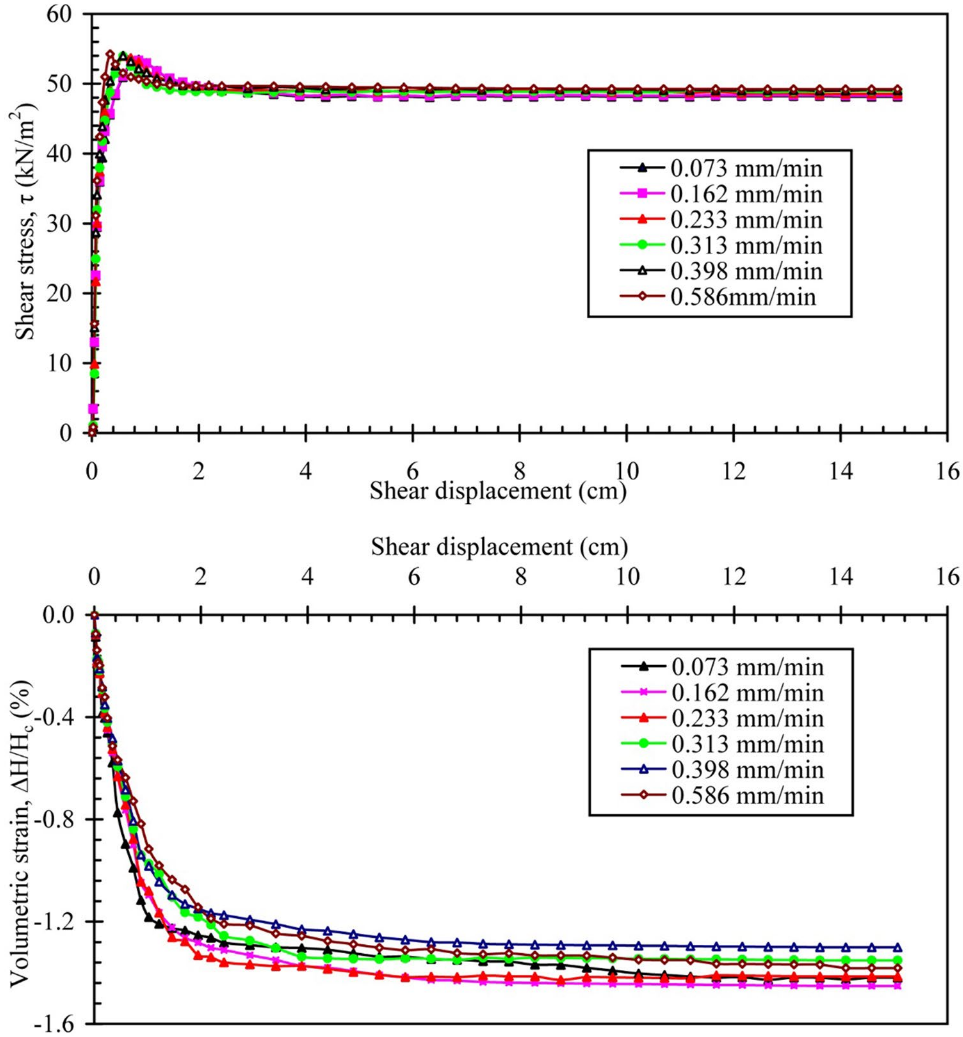
the Clay soil-I was the strongest and the Clay soil-IV was the weakest. The Clay soil-IV showed the high plasticity in its soil's nature, and the Clay soil-III and the Clay soil-II showed the medium plasticity in their soil's nature. Similarly, the Clay soil-I showed the low plasticity in its soil's nature.

Summary of the various shear rate tests of the Clay soil-I, the Clay soil-II, the Clay soil-III, and the Clay soil-IV is presented in Tables 2, 3, 4, and 5. In this table, $\dot{D}$ and σ'_n represent the shear rate and the effective normal stress, respectively. Similarly, τ_r, τ_r/σ_n, $\Delta\tau_r$, $\Delta\phi_r$, and $\Delta H/Hc$ are the residual shear strength, the shear-normal stress ratio at residual state, change in residual strength, change in residual friction angle, and the volumetric strain during the shear, respectively.

Shear behavior

The residual shear strengths of the Clay soil-I were found to vary from 48.13kN/m^2 to 49.24kN/m^2 with the shear rates of 0.073 to 0.586 mm/min (Table 2). The residual shear strengths of the Clay soil-II, the Clay soil-III, and the Clay soil-IV were found to vary in a range of 44.87 to 46.05 kN/m^2, 24.88 to 26.94 kN/m^2, and 8.88 kN/m^2 to 11.85 kN/m^2 for shear rates of 0.073 to 0.586 mm/min (Tables 3, 4, and 5). In the case of the Clay soil-I, the same values of the residual strength (i.e., 48.13 kN/m^2) were recorded for the shear rates of 0.073 mm/min and 0.162 mm/min. The same value of the volumetric strain (i.e., 1.4%) was also obtained with that shear rate of 0.073 mm/min and 0.162 mm/min (Table 2). Similarly, the same value of the residual shear strength and the volumetric strain was found in the shear rates of 0.073 mm/min and 0.0162 mm/min in the cases of the Clay soil-II, the Clay soil-III, and the Clay soil-IV (Tables 3, 4, and 5). In this study, the residual shear strengths (τ_r) for all tested samples were found to remain almost the same for the shear rate range of 0.073 mm/min and 0.162 mm/min (i.e., neutral rate effect) as shown in Tables 2, 3, 4, and 5. This may lead to understand that a clay material exhibits only negligible effect of slower shear rate on the residual shear resistance. Skempton [33] concluded that the effect of shear rates between 0.002 and 0.1 mm/min on residual strength was negligible in clay soils. A neutral rate effect occurs in the silica sand sample [27]. A neutral rate effect occurs in the slow shear rates on kaolin clay and landslide soils having weak clay minerals [1, 2, 7, 11]. Scaringi and Di Maio [32] reported that a neutral rate effect has been confirmed on kaolin, bentonite, and their mixtures with sand in the range of 10^{-6}–10^{-1} mm/min. The neutral rate effect is the exception for the soil undergo shearing [32]. The negligible shear rate effect was observed in dry specimen and on the sand-sized granules; however, strong rate-dependent behavior was observed on gravel-sized mudstones [32]. The findings in this study have been confirmed the conclusions made by the Skempton's [33], Saito et al. [27], Bhat et al. [1, 2], and [11], Scaringi and Di Maio [32].

Fig. 8 Typical results of shear rate tests of Clay soil-I



The residual shear strengths of the Clay soil-I were varied in a range of 48.13 to 49.24 kN/m^2 with shear rates ranging from 0.162 to 0.586 mm/min (Table 2). The residual shear strength of the Clay soil-II, the Clay soil-III, and the Clay soil-IV was found to vary in a range of 44.87 to 46.05 kN/m^2, 24.88 to 26.94 kN/m^2, and 8.88 to 11.85 kN/m^2 for the shear rates of 0.162–0.586 mm/min (Tables 3, 4, and 5). The difference between the residual shear strength at the maximum shear rate of 0.586 mm/min and the minimum shear rate of 0.162 mm/min was recorded 1.11 kN/m^2, 1.18 kN/m^2, 2.06 kN/m^2, and 2.97 kN/m^2 in the cases of the Clay soil-I, the Clay soil-II, Clay soil-III, and Clay soil-IV, respectively (Tables 2, 3, 4, and 5). Therefore, the shear strength of clay soils was a slight increase from its residual shear strength with the increase in the shear rates (i.e., positive rate effect). The shear rate leads to a small increase in the residual strength of clay soils [21]. The residual strength of clay soils from the slip surface of the reactivated landslides was hardly increased with increasing shear rate [42]. Suzuki et al. [24] concluded that the residual strength of Clay soil-I and mud stone was positively influenced by the shear rate of 0.02 to 2.0 mm/min. The residual shear strength of clay soils is slightly increased with the increase in slow shear rates [1, 2, 7, 11]. The soils containing a higher portion of platy-shaped clay minerals show a positive rate effect [32, 35]. This conclusion made in this study has been agreed with the finding of La Gutta [21], Lemos et al. [23], Yatabe et al. [42], Suzuki et al. [34], Bhat et al. [1, 2, 7] and [11], Tika et al. [35], Scaringi and Di mario [32].

Lemos et al. [23] reported that the residual strength of high-plasticity soils increases and decreases for low-plasticity soils with the increase in shear rate. Non-plastic soils show the negative rate effect, and plastic soils show the positive rate effect [28]. The value of the increase in shear strength from its residual state of shear due to the slow shear rates was found to be higher in high-plasticity soils as compared with low-plasticity soils. From the series of test results, the increased in shear strength was observed to be the highest in the Clay soil-IV (i.e., high-plasticity soil), followed by the Clay soil-III and the Clay soil-II (i.e.,

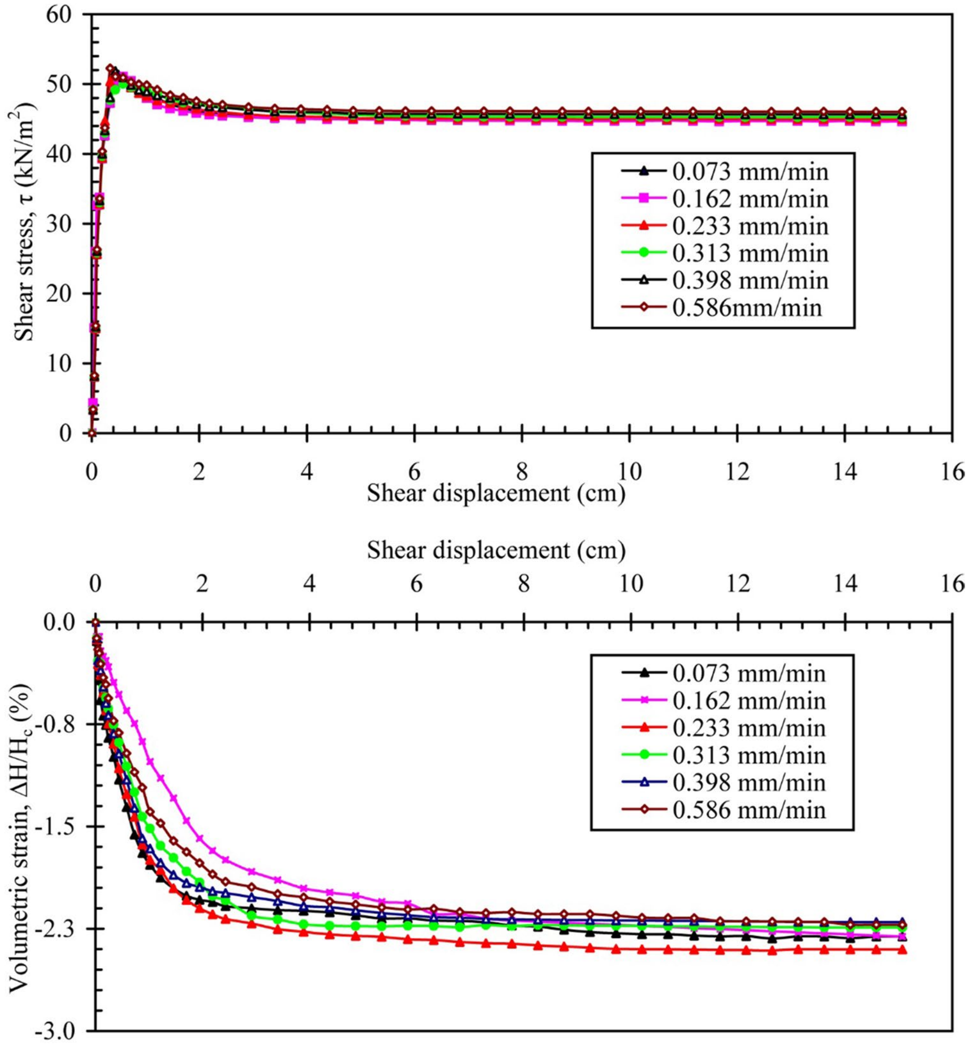


Fig. 9 Typical results of shear rate tests of the Clay soil-II

medium-plasticity soil), and then Clay soil-I (i.e., low-plasticity soil). Hence, it can be concluded that the effect of the shear rates on the residual strength is noticeable for the high-plasticity soils when compared to the low-plasticity soils. From this, it is understood that the effect of shear rates on residual strength will be slightly greater in high-plasticity soils when compared to the low-plasticity soils at the slow share rate of 0.162–0.586 mm/min. These results are agreed with the conclusion made by Skempton [33], Lemos et al. [23], Parathirasv [26], Habibbeygi and Nikraz [16], Lian et al. [22].

Relation between residual friction coefficient (τ_r/σ'_n) and shear rate ($\dot{D}$)

The residual friction coefficient (τ_r/σ'_n) of Clay soil-I was found to vary from 0.491 to 0.502 in a range of shear rate of 0.073 to 0.586 mm/min (Table 2). Similarly, the residual friction coefficient of the Clay soil-II, the Clay soil-III, the Clay soil-IV was found to vary in a range of 0.457 to 0.469, 0.254 to 0.275, and 0.091 to 0.121 with the shear rate of 0.073 mm/min to 0.586 mm/min, respectively (Tables 3, 4, and 5). The relation between residual friction coefficient (τ_r/σ'_n) and shear rate ($\dot{D}$) of the tested clay soils is presented in Fig. 12.

In the case of the Clay soil-I, the same residual friction coefficient (i.e., 0.491) was found with the shear rates of 0.073 mm/min and 0.162 mm/min (Table 2). Similarly, the value of the residual friction coefficient of the Clay soil-II, the Clay soil-III, the Clay soil-IV was observed to be 0.457, 0.254, and 0.091 for the shear rates of 0.073 mm/min and 0.162 mm/min, respectively (Tables 3, 4, and 5). Based on those results, it was understood that the residual friction coefficient of clay soils has not affected by the shear rate up to 0.162 mm/min.

When the shear rates were varied in a range of 0.162 to 0.586 mm/min, the residual friction coefficients of the tested clay soils were found to be affected. The residual friction coefficients of the Clay soil-I, the Clay soil-II, the Clay soil-III, and the Clay soil-IV were found to vary

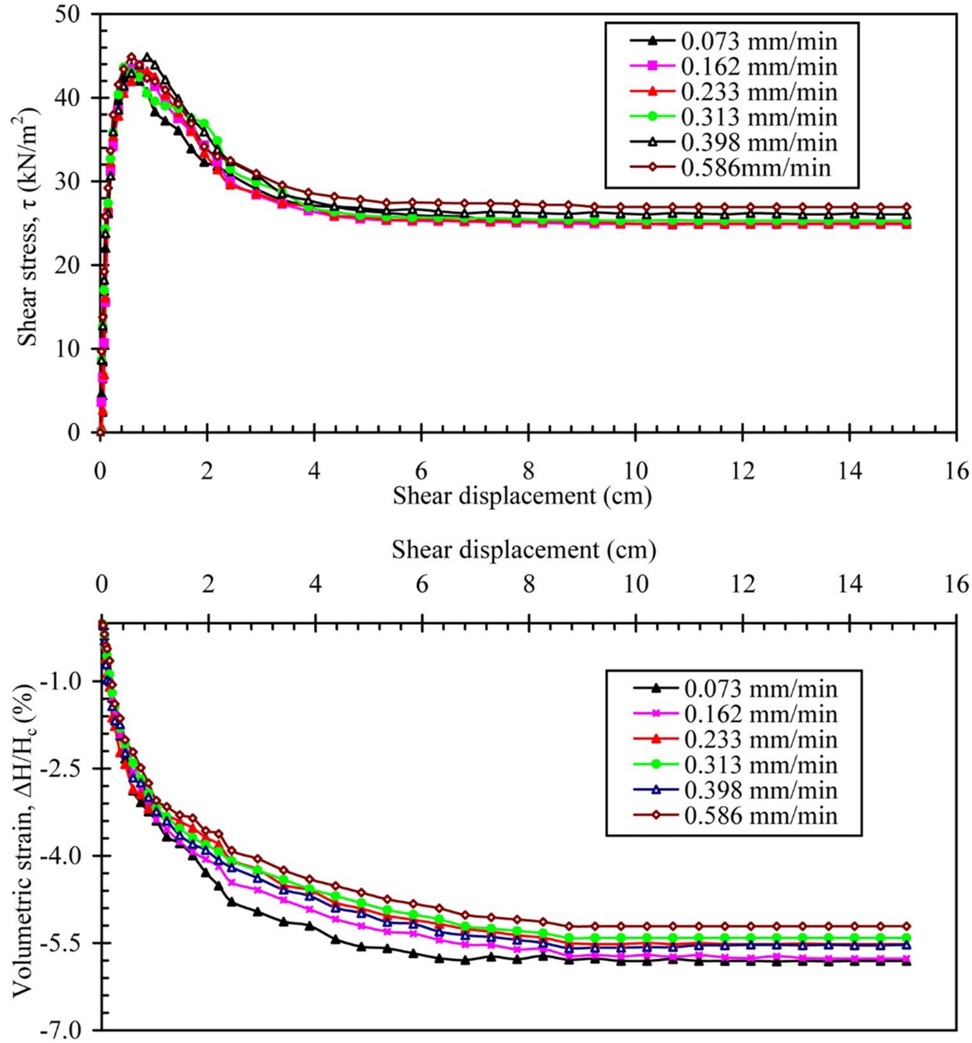


Fig. 10 Typical results of shear rate tests of the Clay soil-III

in a range of 0.491° to 0.502°, 0.457° to 0.469°, 0.254° to 0.275°, and 0.091° to 0.121° with a variation of shear rates from 0.162 mm/min to 0.586 mm/min, respectively. The value of increase in residual friction coefficient for the Clay soil-I, the Clay soil-II, the Clay soil-III, and the Clay soil-IV was found to be 0.011°, 0.012°, 0.021°, and 0.030°, respectively. Therefore, the residual friction coefficient of clay soil is a slight increase when the shear rate is also increased. Gibo et al. [14] stated that the difference in the residual friction coefficient of each sample depends on the shear rate, which is related to the difference in the development/formation of particle reorientation along the shear surface. Lupini [24] reported that the residual friction coefficient increased continuously with the increase in the slow shear rates in the ring shear tests. The results thus obtained in this study are also in close agreements with the finding of Lupini [24]. However, Scaringi et al. [30] reported that the friction coefficient generally decreased with the shear rates of less than or equal to 3 mm/min and increased under high shear rates. The residual friction coefficient was significantly decreased with the increase in shear rates in different steps [17].

Shear rate effect mechanism

The three modes of shearing in soil (i.e., turbulent, transitional, and sliding) were first hypothesized by Lupini et al. [24]. The possible change from sliding to turbulent mode was discussed based on the scanning electron microscope (SEM) techniques [27, 28, 41]. Scaringi et al. [30] reported that the persistence of a polished, slickensided, and regular surface after fast shearing appears to exclude a transition toward turbulent shearing even at low normal stress due to the presence of high-clay fractions. For the shearing rate typically lower than 10 mm/min in usual testing configurations, the turbulent shearing may be excluded [31]. Scaringi et al. [30] also suggested that the transition from rate-strengthening to rate-weakening behavior in both clay-rich and carbonate-rich materials in the rapid-to-very-rapid rate range. A transition from a high-friction regime at a high

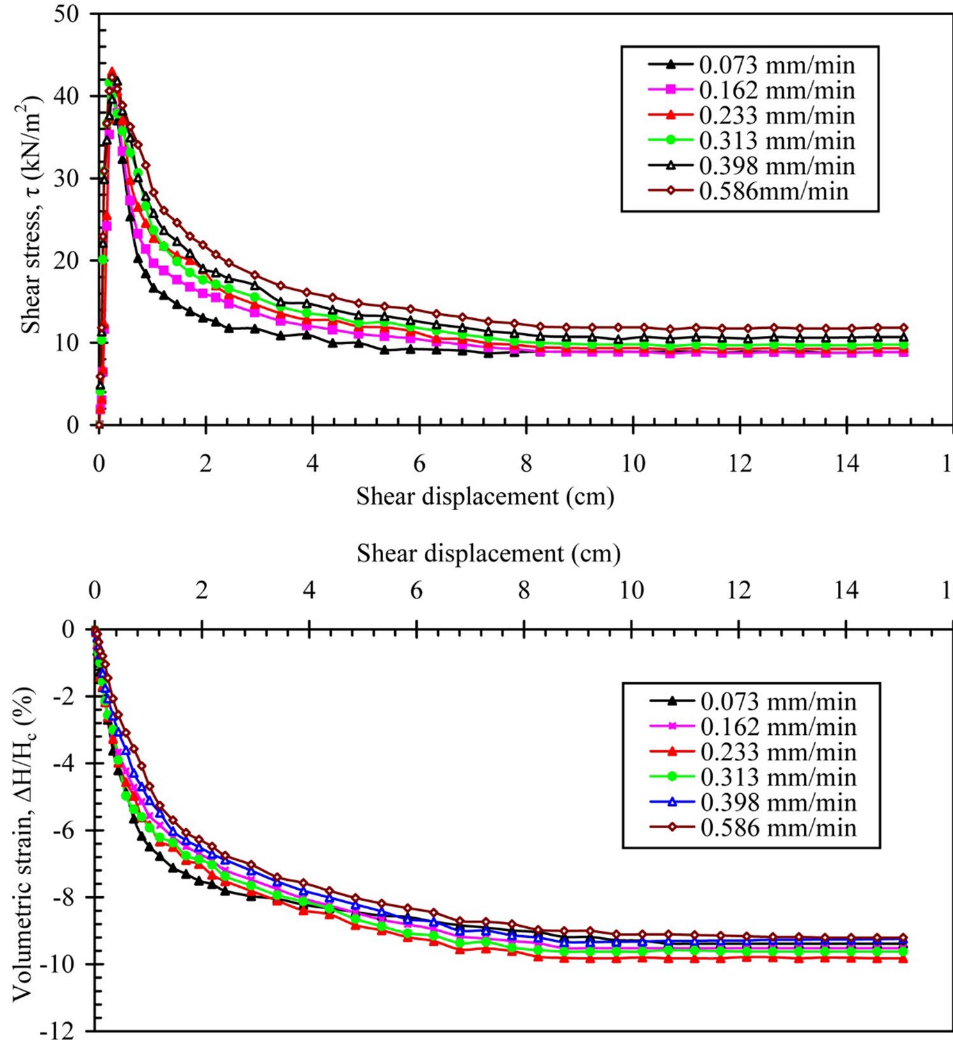


Fig. 11 Typical results of shear rate tests of the Clay soil-IV

Table 2 Summary of shear rate tests of the Clay soil-I

Test no.	$\dot{D}$(mm/min)	σ'_n (kN/m^2)	τ_r (kN/m^2)	τ_r/σ'_n	$\Delta\tau_r$ (kN/m^2)	$\Delta\phi_r$ (degree)	$\Delta H/H_c$ (%)	Rate effect
1-1	0.073	98.1	48.13	0.491	0.00	0.00	– 1.42	Neutral
1-2	0.162	98.1	48.13	0.491	0.00	0.00	– 1.45	Neutral
1-3	0.233	98.1	48.56	0.495	0.42	0.20	– 1.42	Positive
1-4	0.313	98.1	48.94	0.499	0.80	0.38	– 1.35	Positive
1-5	0.398	98.1	49.05	0.500	0.91	0.43	– 1.30	Positive
1-6	0.586	98.1	49.24	0.502	1.11	0.52	– 1.38	Positive

Table 3 Summary of shear rate tests of the Clay soil-II

Test no.	$\dot{D}$ (mm/min)	σ'_n (kN/m^2)	τ_r (kN/m^2)	τ_r/σ'_n	$\Delta\tau_r$ (kN/m^2)	$\Delta\phi_r$ (degree)	$\Delta H/H_c$ (%)	Rate effect
1-1	0.073	98.1	44.87	0.457	0.00	0.00	– 2.31	Neutral
1-2	0.162	98.1	44.87	0.457	0.00	0.00	– 2.31	Neutral
1-3	0.233	98.1	44.95	0.458	0.08	0.04	– 2.40	Positive
1-4	0.313	98.1	45.25	0.461	0.38	0.18	– 2.24	Positive
1-5	0.398	98.1	45.65	0.465	0.78	0.38	– 2.20	Positive
1-6	0.586	98.1	46.05	0.469	1.18	0.57	– 2.22	Positive

Table 4 Summary of shear rate tests of the Clay soil-III

Test no.	$\dot{D}$ (mm/min)	σ'_n (kN/m^2)	τ_r (kN/m^2)	τ_r/σ'_n	$\Delta\tau_r$ (kN/m^2)	$\Delta\phi_r$ (degree)	$\Delta H/H_c$ (%)	Rate effect
1-1	0.073	98.1	24.88	0.254	0.00	0.00	−5.81	Neutral
1-2	0.162	98.1	24.88	0.254	0.00	0.00	−5.77	Neutral
1-3	0.233	98.1	24.96	0.254	0.08	0.04	−5.52	Positive
1-4	0.313	98.1	25.30	0.258	0.42	0.23	−5.41	Positive
1-5	0.398	98.1	26.05	0.266	1.17	0.64	−5.53	Positive
1-6	0.586	98.1	26.94	0.275	2.06	1.12	−5.52	Positive

Table 5 Summary of shear rate tests of the Clay soil-IV

Test no.	(mm/min)	σ'_n (kN/m^2)	τ_r (kN/m^2)	τ_r/σ'_n	$\Delta\tau_r$ (kN/m^2)	$\Delta\phi_r$ (degree)	$\Delta H/H_c$ (%)	Rate effect
1-1	0.073	98.1	8.88	0.091	0.00	0.00	−9.382	Neutral
1-2	0.162	98.1	8.88	0.090	0.00	0.00	−9.517	Neutral
1-3	0.233	98.1	9.35	0.095	0.47	0.27	−9.821	Positive
1-4	0.313	98.1	9.78	0.100	0.90	0.52	−9.620	Positive
1-5	0.398	98.1	10.71	0.109	1.83	1.06	−9.241	Positive
1-6	0.586	98.1	11.85	0.121	2.97	1.72	−9.205	Positive

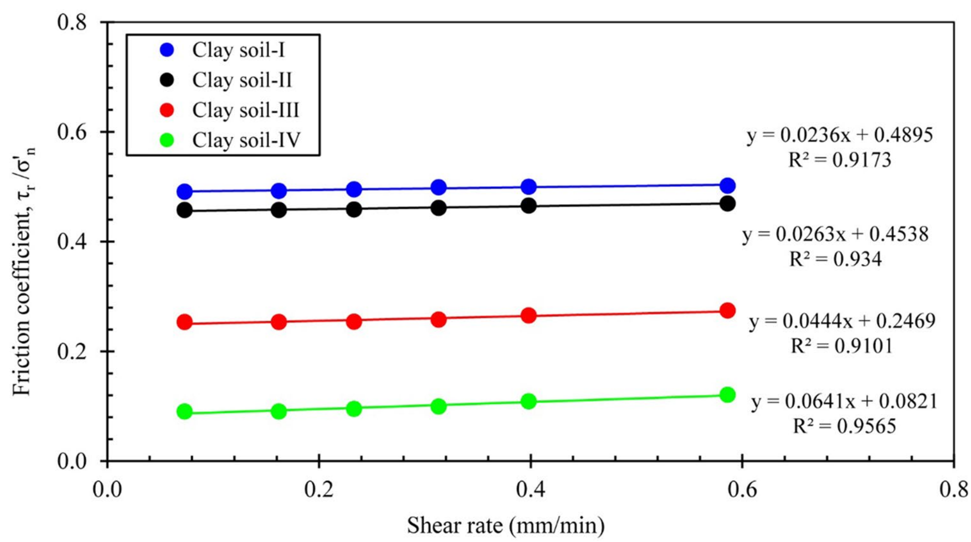


Fig. 12 Relation between residual friction coefficient (τ_r/σ'_n) and shear rate ($\dot{D}$)

displacement rate was observed for saturated gravel-sized granules [19]. In addition, the translation occurred either the rate progressively increased or decreased for shear rate of 0.2–5 mm/s [19].

Shear rate effect mechanism on the residual shear strength of clay soils is not yet fully understood. However, there are two major hypotheses related to shear rate effect mechanisms in most of the studies [1, 2, 11, 19, 28, 33, 35, 41]. The first one is about the generation of excess pore water pressure due to an increase shear rate, which leads to a reduced effective normal stress and decreased shear resistance. Matsui et al. [25] stated that the generated pore water pressure depends on the strain rate; therefore, the change in pore water pressure in the residual strength may depend on shear rates. However, all ring shear tests were conducted in fully drained conditions in this study. Moreover, it has been assumed that there is no volumetric change during shear at the residual state of shear, which means that the generation of chances of excess pore water pressure during test was negligible. However, the results show that the change in volumetric strain for the Clay soil-I, the Clay soil-II, the Clay soil-III, and the Clay soil-IV was found to be in a small range of 1.420 to 1.382%, 2.308 to 2.221%, 5.808 to 5.521%, and 9.517 to 9.205%, respectively, in a shear rate ranging from 0.233 to 0.586 mm/min. If there was an effect of the generation of excess pore water pressure (i.e., change in volumetric strain), the residual shear strength should be decreased. Therefore, the trend of increase in residual shear strength with the increase in shear rates indicates that the increase in strength on clay soils from its residual state of shear was not because of the excess pore water pressure generation along the shear surface. Wang et al. [41] have performed the ring shear tests on dry and saturated landslide soil samples to understand the role of pore water pressure during shear. The similar results were obtained on the dry and saturated landslide soil samples at a constant shear rate [41]. Such conclusions also supported that the generation of excess porewater pressure was not responsible for a slight increase in shear strength from the residual state of shear with the increase in shear rates in the ring shear test.

The second hypothesis is related to the change in shear mode with the variation of the shear rates. During a slow shear rate, shear grains of the shear surface will align parallel to the direction of shear and the shear mode is dominated by inter-granular sliding. When the shearing rate increases, grains within the shear zone will lose their alignment and the shear mode is dominated by turbulent shearing, causing increase in the shear strength [23]. Hu et al. [17] suggested that a change in shear mode could possibly be the mechanism leading to the rather sharp transition between the two friction regimes and also relates to the fluid behavior of mud in the shear zone. The change in shear mode may affect the measurement of the residual friction angle of clay soil materials [27, 28, 34, 35]. Figure 13 shows the concept of shear rate effect mechanism of typical clay soils, which was prepared based on the experimental results of measured residual friction angles with shearing rates of 0.073 mm/min, 0.162 mm/min, 0.233 mm/min, 0.313 mm/min, 0.398 mm/min, and 0.586 mm/min. In this study, the variation of the residual friction angles of the Clay soil-I, the Clay soil-II, the Clay soil-III, and the Clay soil-IV was found to be in a range of 26.21°–26.65°, 24.57°–25.15°, 14.24°–15.36°, and 5.17°–6.89° with the variation of the shear rates, respectively. The increase in the internal friction angles of 0.49°, 0.57°, 1.12°, and 1.72° from their residual friction angles was found to increase at a shear rate of 0.233 mm/min, 0.313 mm/min, 0.398 mm/min, and 0.586 mm/min in the cases of the Clay soil-I, the Clay soil-II, the Clay soil-III, and the Clay soil-IV, respectively (Fig. 13). In general, clay particles or soil grains are aligned in the shear direction and the shear mode is dominated by inter-granular sliding. However, if the shear rate is increased, the shear surface's soil grains will lose their alignment and an increase in the frictional resistance between the soil particles. In addition, the increase in roughness of the shearing surface could be relevant with the increase in residual friction angle from its residual state of shear during the increase in shear rates. In other words, the increase in shearing surface's roughness and the loss of the alignment of the shear surface's soil grains due to high shear rates are responsible for the increase in residual shear strength. Therefore, it can be concluded that the change in shear mode can be considered as the primary cause of the shear rate effect mechanism on residual strength of clay soils. If the microstructure of the shear surface at the end of tests could be observed by laser microscope and scanning electron microscope (SEM) techniques, the roughness of the shear surface due to the change in shear mode could be observed more clearly. However, SEM technique was not considered to observe the slickensides of the slip surface formed with the variation of the shear rate at the end of the ring shear test in this study. Moreover, it could be suggested that a possible mechanism producing the transition

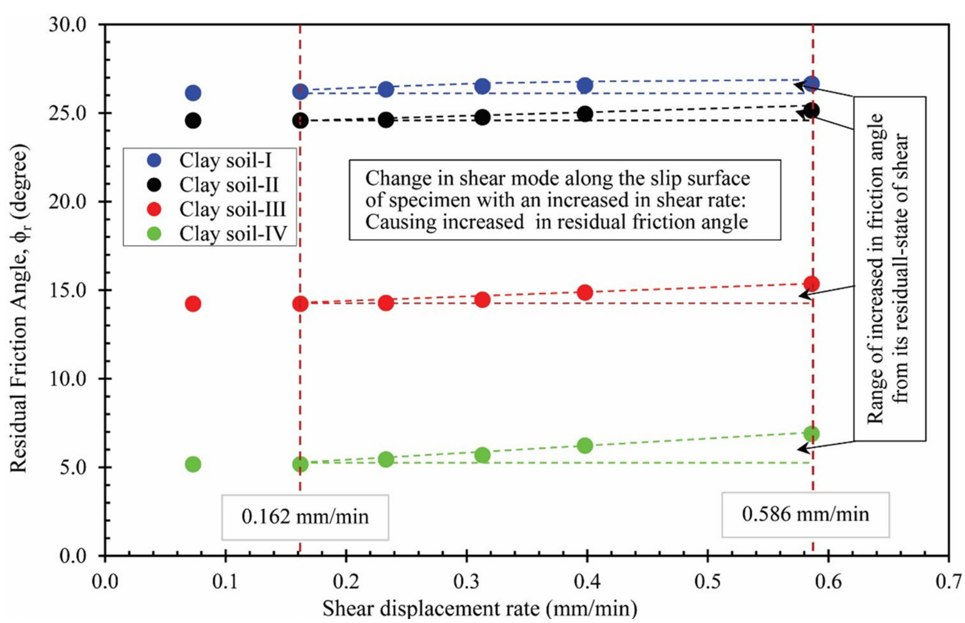


Fig. 13 Shear rate effect mechanism based on experimental results of typical clay soils

from laminar to turbulent flow may also play the significant role in changing the strength of soil with varying shear rates; however, the microstructure study of shear zone's soils in different test conditions is necessary for further better understanding of shear rate effect mechanism in future.

Conclusions

Residual strength parameters of slip zone soil are the important soil parameter for stability analysis and better understanding of the reactivation potential and progressive failure mechanism of reactivated landslides. In this study, a series of ring shear tests were performed on the four typical clay soils (having high-to-low plasticity in its soil natures) to understand the effect of shear rates on the residual strength and the shear rate effect mechanisms on clay soils. The shear rates in the ring shear tests were varied in a range of 0.073–0.586 mm/min. The neutral rate effect and positive rate effect were noted in this study. The main findings were summarized as follows:

1. The high-plasticity soil (Clay soil-IV) was found to have the higher amount of the smectite clay minerals when compared to other presence clay minerals in it. Similarly, the medium-plasticity soils (Clay soil-III and Clay soil-II) were found to present the higher amount of the chlorite and mica clay minerals, respectively.
2. The increase in strength from its residual state of shear of typical clay soils was found to be negligible effect on the shear rates of 0.073 mm/min and 0.162 mm/min (i.e., neutral rate effect).
3. Slightly increase in strength from its residual state of shear of typical clay soils was observed at shear rates of 0.233 mm/min, 0.313 mm/min, 0.398 mm/min, and 0.586 mm/min. (i.e., positive rate effect).
4. The increase in strength from its residual state of shear was slightly higher in high-plasticity soils, with a large difference between the peak strength and residual strength, than in low-plasticity soils.
5. A change in shear mode along the shear surface may be occurred during the change in shear rates. This change in shear mode could be thought as the shear rate effect mechanisms on the residual shear strength of typical clay soils in ring shear test.

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Declarations

Conflict of interest Deepak Raj Bhat declares that he has no conflict of interest.

References

1. Bhat DR, Yatabe R (2015) Effect of shearing rate on residual strength of landslide soils. Eng Geol Soc Territ 2:1211–1215
2. Bhat DR, Yatabe R, Bhandari NP (2014) Slow shearing rates' effect on residual strength of landslide soils. Geotech Spec Publ 236:293–303
3. Bhat DR, Yatabe R, Bhandari NP (2014) Strength recovery from residual-state of shear on soils. Indian Geotech J 44(1):94–100
4. Bhat DR, Bhandary NP, Yatabe R (2014) Creeping displacement behavior of clayey soil in a new creep test apparatus. Geotech Spec Publ 236:275–285
5. Bhat DR, Bhandary NP, Yatabe R (2013) Residual-state creep behavior of typical clayey soils. Nat Hazards 69(3):2161–2178
6. Bhat DR, Bhandary NP, Yatabe R (2013) Study of preexisting shear surfaces of reactivated landslides from a strength recovery perspective. J Asian Earth Sci 77:243–253
7. Bhat DR, Bhandary N, Yatabe R (2013) Effect of shearing rate on residual strength of kaolin clay. Electron J Geotech Eng 18(G):1387–1396
8. Bhat DR, Yatabe R, Bhandari NP (2013) Experimental study of strength recovery from residual strength on kaolin clay. Int J Civil Environ Eng 7(1):76–81
9. Bhat DR, Yatabe R, Bhandari NP (2013) Method of Residual-state creep test to understand the creeping behavior of landslide soils. In: Landslide science and practice, Volume 2: Early warning, instrumentation and monitoring, pp 635–642
10. Bhat DR, Yatabe R, Bhandari NP, Tiwari RC (2012) A new concept of residual-state creep test to understand the creeping behavior of claye soils. Geotech Spec Publ 225:683–692
11. Bhat DR (2021) Shearing rate effect on residual strength of typical clay soils in ring shear test. In: Understanding and reducing landslide disaster risk: testing, modeling and risk assessment, vol 4, pp 365–369
12. Bishop AW, Green E, Garge VK et al (1971) A new ring shear apparatus and its application to the measurement of residual strength. Geotechnique 21(4):273–328
13. Duong NT, Suzuki M, Hai NV (2018) Rate and acceleration effects on residual strength of kaolin and kaolin–bentonite mixtures in ring shearing. Soils Found 58:1153–1172
14. Gibo S, Egashira K, Ohtsubo M (1987) Residual strength of smectite-dominated soils from the Kamenose landslide in Japan. Can Geotech J 24(3):456–462
15. Gratchev I, Sassa K (2015) Shear strength of clay at different shear rates. J Geotech Environ Eng 141(5):06015002–06015011
16. Habibbeygi F, Nikraz H (2018) Effect of shear rate on the residual shear strength of pre-sheared clays. Cogent Geosci 4(1):1–9
17. Hu W, Wang G, Scaringi G, McSaveney M, Hicher P-Y (2017) Shear resistance variations in experimentally sheared mudstone granules: a possible shear-thinning and thixotropic mechanism. Geophys Res Lett 44:11040–11050
18. Hu W, Scaringi G, Xu Q, Van Asch TWJ, Huang R, Han W (2018) Suction and rate-dependent behaviour of a shear-zone soil from a landslide in a gently-inclined mudstone-sandstone sequence in the Sichuan basin, China. Eng Geol 237:1–11

19. Jurko J, Sassa K (2008) Hiroshi Fukuoka Study on seismic behavior of nonplastic silt by means of ring-shear apparatus. Landslides 5:189–201
20. Kimura S, Nakamura S, Vithana SB, Sakai K (2014) Shearing rate effect on residual strength of landslide soils in the slow rate range. Landslides 11(6):969–979
21. La Gatta DP (1970) Residual strength of clays and clay shales by rotation shear tests. In: Harvard soil mechanics series, no. 86, Cambridge, USA, p 204
22. Lian B, Wang X, Peng J, Huang Q (2020) Shear rate effect on the residual strength characteristics of saturated loess in naturally drained ring shear tests. Nat Hazards Earth Syst Sci 20:2843–2856
23. Lemos L, Skempton AW, Vaughan PR (1985) Earthquake loading of shear surfaces in slopes. In: Proc 11th ICSFE, San Francisco, vol 4, pp 1955–1958
24. Lupini JF, Skinner AE, Vaughan PR (1981) The drained residual strength of cohesive soils. Geotechnique 31(2):181–213
25. Matsui T, Ohara H, Ito T (1977) Effect of dynamic stress history on mechanical characteristics saturated clays. J Jpn Soc Civ Eng 257:41–51 (**in Japanese**)
26. Parathiras AN (1994) Displacement rate effects on the residual strength of soils. PhD Thesis, University of London. (Imperial College of Science, Technology and Medicine)
27. Saito R, Fukuoka H, Sassa K (2006) Experimental study on the rate effect on the shear strength. In: International symposium disaster mitigation of debris flows, slope failures and landslides, pp 421–427
28. Saito R, Sassa K, Fukuoka H (2007) Effects of shear rate on the internal friction angle of silica sand and bentonite mixture samples. J Jpn Landslide Soc 44(1):33–38 (**In Japanese with English abstract**)
29. Sassa K, Fukuoka H, Wang G (2004) Naohide Ishikawa, Undrained dynamic-loading ring-shear apparatus and its application to landslide dynamics. Landslides 1:7–19
30. Scaringi G, Hu W, Xu Q, Huang R (2018) Shear-rate-dependent behavior of clayey Bimaterial interfaces at landslide stress levels. Geophys Res Lett 45:766–777
31. Scaringi G, Hu W, Xu Q (2018) Discussion on: "Experimental study of residual strength and the index of shear strength characteristics of clay soil" [Eng.Geo. 233:183–190]. Eng Geol 242:218–221
32. Scaringi G, Di Maio C (2016) Influence of displacement rate on residual shear strength of clays. Proc Earth Planet Sci 16:137–145
33. Skempton AW (1985) Residual strength of clays in landslides, folded strata, and the laboratory. Geotechnique 35(1):3–18
34. Suzuki M, Yamamoto T, Tanikawa K (2001) Variation in residual strength of clay with sharing speed. Research report, Yamagushi University 52(1):45–49
35. Tika TE, Vaughan PR, Lemos LJ (1996) Fast shearing of preexisting shear zones in soil. Geotechnique 46(2):197–233
36. Tika TE (1999) Ring shear tests on a carbonate sandy soil. Geotech Test J 22(4):342–355
37. Tiwari B, Marui H (2004) Objective oriented multistage ring shear test for shear strength of landslide soil. J Geotech GeoenvironEng 130(2):217–222
38. Vithana SB, Nakamura S, Kimura S, Gibo S (2012) Effects of over consolidation ratios on the shear strength of remoulded slip surface's soils in ring shear. Eng Geol 131–132:29–36
39. Wang Y, Cong L (2019) Effects of water content and shearing rate on residual shear stress. Arab J Sci Eng 44:8915–8929
40. Wang L, Han J, Liu S et al (2020) Variation in shearing rate effect on residual strength of slip zone soils due to test conditions. Geotech Geol Eng 38:2773–2785
41. Wang G, Suemine A, Schulz WH (2010) Shear-rate-dependent strength control on the dynamics of rainfall-triggered landslides, Tokushima Prefecture, Japan. Earth Surf Process Landforms 35(4):407–416
42. Yatabe R, Yagi N, Enoki M et al (1991) Strength characteristics of landslide clay. J Jpn Landslide Soc 28(1):9–16 (**in Japanese with English abstract**)
43. Yokota K, Yatabe R, Yagi N (1995) Strength characteristics of weathered serpentine, Doboku Gakkai Ronbunshu, No. 529/III-33, 155–163 **(in Japanese with English abstract)**