Determination of Residual Strength of Soils for Slope Stability Analysis: State of the Art Review

Chen Fang¹, Hideyoshi Shimizu², Tatsuro Nishiyama*³ and Shin-Ichi Nishimura³

¹ The United Graduate School of Agricultural Science, Gifu University, 1-1 Yanagido, Gifu 501-1193, Japan
² Emeritus Professor, Gifu University, 1-1 Yanagido, Gifu 501-1193, Japan
³ Faculty of Applied Biological Sciences, Gifu University, 1-1 Yanagido, Gifu 501-1193, Japan

ABSTRACT
Slope stability is always one of the greatest issues of concern in geotechnical engineering. In slope stability analyses, the residual strength of slip zones is one of the most important parameters for understanding the reactivation mechanisms and for evaluating the stability of slopes. The kinds of soils, the situations of the soils, and the test conditions are the three main aspects that affect the residual strength. Among the test conditions, the selection of the shear testing apparatus, the normal stress, the overconsolidation ratio, the shear rate, and the acceleration are the main critical factors that affect the residual strength of soils. This paper firstly presents a systematic literature review of the factors that influence the residual strength of soils under certain test conditions, which can help obtain the residual strength accurately and easily in a geotechnical research. The paper also summarizes the available indexes, such as the Atterberg limits, for determining the residual strength. Moreover, this paper highlights future research challenges with an aim to clarify the effect of acceleration on the residual strength in a wider range which has not been well researched, but which needs to be explored further.

Keywords
effect of acceleration, influencing factors, residual strength, slope stability analysis

1. Introduction
Landslides comprise one of the Earth’s most serious types of natural disasters, causing the loss of human life and great damage to the social economy. Therefore, slope stability analyses are especially important in geotechnical engineering. The residual strength is a crucial parameter in these analyses for the design of foundations for reservoir embankments, roads, and other infrastructure projects, particularly considering the effect of large earthquakes on the settlement of foundations (Insley et al., 1977; Marcuson et al., 1990).

As early as 1936, people recognized the problem that the average shear stress on the sliding surfaces of the landslides measured at a site or in the laboratory was much smaller than the actual shear strength on these surfaces. In other words, accurate stability analyses cannot be generated when using the actual shear strength as the value for slope stability analyses of landslides. It was not until 1964 that this issue was systematically discussed in an article entitled "Long-term stability of clay slopes” (Skempton, 1964), and that the idea of residual strength was brought to public attention. The residual strength of soils is usually defined as the minimum and constant drained shear strength at which a soil experiences a large shear displacement under a given normal stress, as shown in Figure 1. Since then, many researchers, like Bishop (1971) and Cullen and Donald (1971), have focused on the study of residual strength. The determination and application of the residual strength gradually became a hot topic in geotechnical engineering. The residual strength is dependent not only on the kinds of soils, including the material, the size and shape of the...
particles, the surface roughness, and so on, but also on the situations of the soils, including the density, the water content, and the structure of the framework, and the testing conditions, including the selection of the shear testing apparatus, the normal stress, the overconsolidation ratio, the shear rate, the acceleration, and so on (Suzuki, 1998). The residual strength is mainly applied for two purposes. One is for calculating the settlement amount of a slope when an earthquake strikes (Newmark, 1965). The other is for evaluating the stability of a slope which has experienced a landslide in the past (Skempton, 1985).

By analyzing the residual shearing mechanism of different grades of synthetic soil and natural soil, Lupini et al. (1981) found that different types of residual shear behavior and different shearing mechanisms occur in cohesive soils with an increase in the amount of clay content in the soil. Through a study on the changes in the structure and strength attenuation after soil shearing, three kinds of residual shear modes, namely, turbulent mode, transitional mode, and sliding mode, were established based on the proportion of platy, low-friction particles and rotund particles present in the soil. Among them, the turbulent mode mainly occurs in soils having a high proportion of rotund particles or platy particles with high interparticle friction, in which the phenomenon of particle orientation does not occur. This mode has high residual strength which depends mainly on the shape and the packing of the rotund particles, rather than on the coefficient of interparticle friction. The post-peak intensity attenuation is mainly due to the contact relationship between the particles and the relative adjustment of the relative position. The shear bands forming in this type of soil have different porosities and are significantly altered by the subsequent stress history. The sliding mode occurs in soil composed of a high proportion of platy, low-friction particles. This mode has low shear strength, and the residual strength mainly depends on the mineralogy, the pore water chemistry, and the coefficient of interparticle friction. After the occurrence of residual shear, a low shear strength shear plane, formed by the orientation of the particles, is produced in the soil. The post-peak intensity attenuation is the result of the grain orientation alignment, and the shear bands are generally unaffected by the subsequent stress history. The transitional mode is between the two other kinds of residual shear types, described above, and occurs in soils with no dominant particle shape. For this type, the residual strength is very sensitive to small changes in the grading of the soils. Skempton (1985) also provided the relationship between the residual strength and the clay fraction. He pointed out
that if the clay fraction is less than 25%, the residual strength of the soils is mainly affected by the fractions of sand and silt. If the clay fraction is more than 50%, the residual strength is affected almost entirely by the clay minerals, and the further increase in clay fraction has little effect. If the clay fraction lies between 25% and 50%, there is a ‘transitional’ type of behavior whereby the residual strength is affected by the proportion of clay particles as well as their properties.

When a slope is being analyzed and judged as safe or not, the kinds and the situations of the soils have been already determined; the operations among the test conditions seems more important in the judgement process. Consequently, it is imperative to determine the residual strength exactly and objectively by regulating the test conditions for each case, in order to judge the stability of the earthworks (e.g., cuttings, embankments, and road). A review of the main influencing factors that affect the residual strength of soils under different test conditions is presented, and an attempt is made to summarize the reason for how the residual strength is affected by each influencing factor from fundamental. Meanwhile, the possible indexes, like the Atterberg limits, clay fraction, and so on, for determining the residual strength are also summarized. This study may contribute to the future development of slope stability analyses.

2. Historical background of slope stability analysis

The stability of earthworks and natural slopes is always a matter of concern to geotechnicians, including practitioners and researchers. The stability of any slope is determined by the balance of shear stress and shear strength. If the force available to resist motion is smaller than the force driving the motion, the slope is considered to be unstable. Two methods are normally used in slope stability analyses, namely, the limit equilibrium method (LEM) and the finite element method (FEM). LEM was developed in the 1930s. Due to its simplicity, which only requires a simple Mohr-Coulomb soil model, LEM continues to be the most commonly used approach (Fellenius, 1936; Janbu, 1954; Bishop, 1955; Morgenstern and Price, 1965; Hammouri et al., 2008; Ali, 2015). However, when using LEM to analyze slopes, calculative difficulties and numerical inconsistencies may occur in locating the critical slip surface (depending on the geology). Therefore, the other method, FEM, caters to the needs of research. FEM obtained its real impetus in the 1960s through developments by researchers (Hinton and Irons, 1968). As personal computers have become more readily available, FEM has been increasingly used in slope stability analyses (Potts et al., 1990; Matsui and San, 1992; Lane and Griffiths, 2000; Hammouri et al., 2008; Ali, 2015). One of the advantages of FEM is that no assumption is required as to the shape or location of the critical failure surface. Besides that, the method can be easily applied to calculate the stresses, motion, and pore water pressures in embankments and the failure induced by leakage as well as to monitor the progressive failure (Hammouri et al., 2008). It should be pointed out that LEM has long been established as the industry standard due to its ability to provide simpler and faster analyses. This gives LEM a slight edge over FEM, which requires the tedious input of all the input parameters. Therefore, it is necessary to consider the actual situation when choosing which method to use for analyzing slope stability. Landslides generated by the failure of slopes are usually astounding, often destructive, and sometimes even fatal. Thus, it is necessary to gain the precise value of the residual strength in order to judge whether the slope is safe or not (Insley et al., 1977 and Marcuson et al., 1990).

3. Selection of shear testing apparatus to measure the residual strength

To determine the relevant geotechnical parameters in a design case, laboratory tests to simulate the field load conditions as closely as possible should be carried out (Kjellmann, 1951). In laboratory tests, the shear strength is commonly determined by three main methods, namely, the triaxial shear test, the direct shear box test, and the ring
shear test, among which, the triaxial shear test is the most widely used shear test. It is popular for its ability to control the drainage conditions and to determine the pore water pressure. However, to determine the residual strength of the soil by the triaxial apparatus, the strain that can be applied to the specimen is limited, particularly for slip zone soils containing a certain amount of coarse-grained particles (Chen and Liu, 2014). Moreover, it is difficult to measure the residual strength of soil because the triaxial shear test cannot measure the strength along the sliding surface. The direct shear box test and ring shear test, on the other hand, can measure the residual strength of soils. After comparing the results of ring shear tests (La Gatta, 1970; Bishop et al., 1971) and direct shear box tests (So and Okada, 1978), the residual strength was found to be the same in spite of the different shear testing apparatuses. Townsend and Gilbert (1973) also concluded that there was no significant difference in residual strength between the values obtained from direct shear box tests or ring shear tests on disturbed samples. However, compared with the direct shear box apparatus, the ring shear apparatus could shear the soil continuously in one direction for any magnitude of displacement without changing the cross-sectional area of the samples. This allows for the full orientation of the particles parallel to the direction of shear, which determines a true residual strength condition (Stark and Vettel, 1992). Therefore, the ring shear test is recommended for use in obtaining the residual strength of soils.

Since the 1920s, many scholars and research institutions have been working on the development of ring shear testing equipment with a simple structure, convenient operation, and easy sample preparation (Hong et al., 2009). They have developed various types of ring shears. The earliest original ring shear testing apparatuses in the world were mainly single-ring apparatuses (Hong et al., 2009). However, the defect of this type of device is that the shear failure usually does not occur inside the soil sample, but appears near the rotary compression plate, and does not guarantee the uniform distribution of the radial stress and strain along with the cylindrical sample, resulting in the measured values not reflecting the true mechanical properties produced in the soil samples. Hvorslev (1939) developed an early true ring shear test apparatus by designing a monolithic single-ring shear box in a circular shear box for which the top and bottom are separated. These early ring shear apparatuses were all stress-controlled. In the decades that followed, the development of the ring shear apparatus almost ceased. Due to the rise in residual strength research in the 1960s and the demands of social development, the study of the ring shear apparatus was reignited. Based on the design concept of Hvorslev (1939), Bishop et al. (1971), Bromhead (1979), Sassa (1997), Sassa et al. (2004), and other scholars developed the ring shear apparatus further. However, Bishop’s ring shear apparatus and Bromhead’s ring apparatus are comparably popular due to the simplicity of their operation, their reasonable cost, and their availability compared to other models developed since then. Nowadays, modern high-precision ring shears are being developed which can simulate changes in stress and pore water pressure and possible liquefaction phenomena during the tests under earthquake and groundwater fluctuations through fast loading systems and high-speed data recording equipment. Table 1 summarizes the typical parameters of the representative ring shear apparatuses. It is seen that the parameters of the ring shear apparatuses have been developed along with time, which may be due to the demands of the precise researches. The research team at DPRI (Disaster Prevention Research Institute), Kyoto University, is presently the most representative, especially for developing the DPRI-6 (Sassa, 1997) and DPRI-7 apparatuses (Sassa et al., 2004), which can be employed to investigate the characteristics of the slope before and after instability failure. In addition, according to the ring shear apparatuses listed in Table 1, the maximum normal stress and the maximum shear rate can reach 3000 kPa and 180,000 mm/min, respectively, which could be used to simulate most kinds of landslides in most situations.
Table 1 Typical parameters of representative ring shear apparatuses

| Author(s)          | Shear box | Inner diameter (cm) | Outer diameter (cm) | Max. height of sample (cm) | Shear area (cm²) | Max. normal stress (kPa) | Max. shear speed (mm/min) | Max. data acquisition rate (reading/sec) |
|--------------------|-----------|---------------------|---------------------|---------------------------|-----------------|--------------------------|---------------------------|----------------------------------------|
| Bishop et al. (1971) | 10.16     | 15.24               | 1.9                 | 101.34                    | 980             | -                        | -                         | -                                      |
| Bromhead (1979)     | 7.0       | 10.0                | 0.5                 | 40.05                     | 200             | -                        | 44.52                     | 1000                                   |
| Hungr and Morgenstern (1984) | 22.0     | 30.0               | 2.0                 | 326.73                    | 200             | 60,000                   | 60,000                    | 1000                                   |
| Tika (1989)         | 10.16     | 15.24               | 1.9                 | 101.34                    | 980             | 660                      | 5598                      | 1000                                   |
| Garga and Sendano (2002) | 9.0       | 13.3                | 2.0                 | 72.45                     | 980             | 3000                     | 134,400                   | 2000                                   |
| Sassa (1997)        | 25.0      | 35.0                | 3.0                 | 471.24                    | 660             | 500                      | 180,000                   | 1000                                   |
| Sassa et al. (2004) | 27.0      | 35.0                | 2.88                | 389.56                    | 27.0            | 35.0                     | 2.88                      | 35.0                                   |

4. Effect of normal stress on residual strength

Eid et al. (2016) summarized that to simulate first-time or reactivated landslides precisely, values of normal stress between 10 to 700 kPa should be considered. Extensive shear testing procedures have been conducted to determine the drained residual strength of soils in a wide range of normal stress. A lot of literature (La Gatta, 1970; Bishop et al., 1971; Hawkins and Privett, 1985; Tiwari and Marui, 2005) has shown that the residual strength increases with an increasing normal stress, and that the value of \( \tau_R / \sigma_N \) (\( \tau_R \): residual strength; \( \sigma_N \): normal stress), called the friction angle ratio, remains almost the same with the increase or decrease in normal stress as long as it is more than 100 kPa. When the normal stress is lower than 100 kPa, the residual strength changes sharply. On the other hand, it has long been pointed out that the shear strength envelopes of plastic soils are nonlinear in the low normal stress range of \( \sigma_N < 50 \) kPa (Penman, 1953; Ponce and Bell, 1971, Charles and Soares, 1984; Skempton, 1985; Day and Axten, 1989; Maksimovic, 1989). The reason why the residual strength is not stable at low normal stress can be found in Gibo et al. (1987). They explained that the degree of orientation is lower at low normal stress by the X-ray diffraction technique, which results in higher residual strength through smectite-dominated soils. Eid et al. (2016) also pointed out the phenomenon whereby the curvature or nonlinearity significantly decreases at effective normal stresses higher than 200 kPa, as shown in Figure 2, and explained that the nonlinear phenomenon in low normal stress ranges can be ascribed to orienting most of the clay particles parallel to the direction of shear through a total of 50 clay, silt, mudstone, and shale samples. Therefore, to obtain the residual strength accurately, high normal stress is recommended as one of the test conditions for use in the shear test.

5. Effect of overconsolidation ratio on residual strength

To obtain the residual strength of soils, it is necessary to consolidate the sample before shearing (Bishop et al., 1971; Bromhead, 1979). Some literature has focused on the relationship between the residual strength and the overconsolidation ratio of soils (Skempton, 1964; La Gatta, 1970; Bishop et al., 1971; So and Okada, 1978; Vithana et al, 2012; Li et al, 2017). From Figure 3 (So and Okada, 1978; Li et al., 2017), it is found that, at most normal stress levels, there is no significant difference in residual strength from the different overconsolidation ratios and
there is only a small increase in residual strength with an increase in the overconsolidation ratios under the normal stress of 50 kPa, which could be analyzed similarly to the effect of low normal stress. Li et al. (2017) emphasized that the effect of overconsolidation on the residual strength can be ignored. Skempton (1964) also stressed that the value of the residual strength acquired from laboratory tests is almost the same whether through the condition of normal consolidation or overconsolidation, but that the time required to obtain the residual strength by normal consolidation is much longer than that by overconsolidation. That is to say, to obtain the residual strength effectively, it is better to consolidate the samples by the overconsolidation condition. Some researches were carried out to clarify the relationship between the residual strength and the overconsolidation ratio using the ring shear test (La Gatta, 1970; Bishop et al., 1971; Yuan et al, 2019), and So and Okada (1978) carried out their study to clarify the relationship using the direct shear box. Comparing the results, a conclusion was made that, regardless of the test method, the residual strength is independent of the overconsolidation ratio. So and Okada (1978) also pointed out that since all particle structures already have parallel orientation structures at the residual strength, the effect of the overconsolidation ratio on the residual strength can be ignored.
6. Effect of shear rate on residual strength

The effect of the shear rate on the residual strength is an interesting and practical topic, which has important scientific significance for the formation mechanism of high-speed landslides and for the prediction of the landslide displacement time and slips (Dai et al., 1998). A better understanding of the rate effect on the residual strength of soils would be beneficial for predicting and evaluating the behavior of reactivated landslides. Due to the above advantages of the ring shear test, the ring shear apparatus was used to conduct research on the effect of the shear rate on the residual strength, instead of direct shear box tests. In past decades, the effects of high and low shear rates on the residual strength of various soils were extensively investigated. Tika et al. (1996) conducted fast ring shear tests on a wide range of natural soils and named three types of rate effects on the residual strength, namely, a positive rate effect (an increase in residual strength with an increasing shear rate), a neutral rate effect (a constant residual strength regardless of the shear rate), and a negative rate effect (a decrease in residual strength when sheared at higher speeds). Table 2 presents a summary of the previous studies on the effect of the shear rate on the residual strength. It is seen that a wide range in shear rates was studied, and that a neutral rate effect usually occurs when the slow shear rate is used. A fast shear rate, due to high-speed shearing, may crush the soil particles. Therefore, the grain size distribution and the grain shapes will be changed due to the rapid crushing (Fukuoka and Sassa, 1991); evident effects are also summarized in Table 2. Although researches on the effect of the shear rate on the residual strength have been extensively conducted, there is still no consistent theoretical description that illustrates the rate effect on the residual strength. This may be a result of the differences in the kinds of soils and the test conditions applied in the various researches. Differences in the clay content or particle shape will lead to different shear modes, resulting in different rate effects (Lupini et al., 1981; Skempton, 1985; Tika et al., 1996). Some reasons for the effect of the shear rate on the residual strength have been proposed. A positive rate effect can be explained by three aspects, namely, the change from sliding mode to turbulent mode (e.g., Skempton, 1985; Tika et al., 1996; Bhat et al., 2013), the crushing of round particles (Fukuoka and Sassa, 1991), and the shear viscosity effect (Tika et al., 1996; Carrubba and Colonna, 2006). In contrast, a negative rate effect in fast shear rate can be explained the delayed dissipation of excess pore water pressure (e.g., Skempton, 1985; Parathiras, 1995; Li et al., 2013). Looking at Table 2, however, it is clearly seen that low shear rates will decrease the effect of the shear rate on the residual strength. The residual strength is not affected by the shear rate if the rate is less than 0.1 mm/min.

7. Effect of acceleration on residual strength

The damage of earthquakes can be catastrophic; they can destroy the stability of buildings, embankments, and so on. In recent years, many countries have established accelerometers and have obtained seismic records. Based on these records, some of the maximum accelerations on the ground surface are reported to have exceeded 980 cm/sec² (Inukai, 2008). Field observations show that the sliding speed of a soil block is not constant in the residual state. Dunong et al. (2018) pointed out that whether the acceleration will affect the residual strength of the soil should be studied. Although the rate effect is a fundamental factor affecting the stability of landslides, it will be more precise for simulating the field load conditions changes if the effect of the acceleration is considered in the analysis. In slope stability analyses, a lot of literature (Newmark, 1965; Gazetas et al., 2009; Xu et al., 2011; Korzec, 2016 and Fang et al., 2018) has considered the impact of acceleration on the slope stability. However, little information on how the acceleration influences the residual strength is available. Duong et al. (2018) pointed out that the acceleration effects on the residual strength of kaolin and kaolin-bentonite mixtures can be disregarded. In their research, Duong et al. on the residual strength. However, compared with the maximum acceleration of 980 cm/sec², these values are too low to completely represent the effect of acceleration on the residual strength. As explained by the above-mentioned
effect of the shear rate on the residual strength, the effect can be ignored with a slow shear rate, whereas a fast shear rate brings about great qualitative changes in the residual behavior (Skempton, 1985; Tika and Huschinson, 1999). Similarly, when the acceleration is strong, it may possibly affect the residual strength. Thus, more studies on the acceleration effect on the residual strength need to be conducted in the future.

### Table 2 Previous studies of effects of shear rate on residual strength

| Reference                  | Range in shear rate (mm/min) | Conclusion                                                                 | Sample                                      |
|----------------------------|------------------------------|---------------------------------------------------------------------------|---------------------------------------------|
| Skempton, 1985             | 0.0001 – 700                 | A neutral rate effect occurs in the slow rates of displacement; a positive or negative rate effect occurs at rates faster than about 100 mm/min. | Clay                                        |
| Fukuoka and Sassa, 1991    | 6 – 60000                    | A slight positive rate effect occurs in sandy material, whereas a strong positive rate effect occurs in clayey material, especially from 6 mm/min to 60 mm/min. | Sandy and clayey materials                  |
| Parathiras, 1995           | 0.009 – 600                  | A positive rate effect.                                                   | Landslide soil                              |
| Tika and Hutchison, 1999   | 0.0145– 2600                 | A negative rate effect occurs at rates of shearing greater than 100 mm/min. | Landslide soil                              |
| Saito et al., 2006         | 0.6 – 600                    | A neutral rate effect occurs in the silica sand sample; however, a negative rate effect occurs in the illite and bentonite mixture sample. | Silica sand, Silica sand mixed with illite or bentonite |
| Suzuki et al., 2007        | 0.02 and 1                   | A positive rate effect.                                                   | Clay                                        |
| Khosravi et al., 2013      | 0.018 and 4.5                | A positive rate effect occurs at the beginning; with continued fast shearing, a negative rate effect comes out. | Kaolinite clay                              |
| Kimura et al., 2013        | 0.01 and 0.5                 | A neutral rate effect.                                                   | Clay-rich and silt/sand-rich soil           |
| Li et al., 2013            | 6, 60 and 600                | The rate effects (positive, neutral or negative) are guided by the inherent properties of the soils. | Landslide soil                              |
| Bhat, 2013; Bhat and Yatabe, 2015 | 0.073 – 0.586 | A neutral rate effect occurs during 0.073 mm/min to 0.162 mm/min, and a positive rate effect occurs after the shear rate of 0.233 mm/min. | Kaolin clay                                 |
| Gratchev and Sassa, 2015   | 12 – 300                     | A negative rate effect.                                                   | Clayey soil                                 |
| Searingi and Di Maio, 2016 | 10^{-4} – 10^{-1}           | A neutral rate effect has been confirmed in the range of 10^{-4} – 10^{-1} mm/min. | Kaolin, bentonite, their mixtures with sand |
| Suzuki et al., 2017        | 0.02 – 20                    | A neutral rate effect occurs at cement contents greater than 2% in the mixture of cemented kaolin. | Kaolin and kaolin mixed with cement         |
| Li et al., 2017            | 0.06 – 30                    | A neutral rate effect occurs up to 10.00 mm/min, and a negative rate effect occurs after 10 mm/min. | Silty sand                                  |
| Lian et al., 2018          | 0.1 and 1                    | A negative rate effect.                                                   | Loess deposits                              |
| Wang and Cong, 2019        | 0.5, 5 and 50                | A positive rate effect.                                                   | Landslide soil                              |
8. Relation with the available indexes

The residual frictional angle of slip zones is one of the most important parameters for understanding the reactivation mechanisms and for evaluating slope stability. However, the performance of laboratory tests to determine the residual frictional angle through shear testing is complex and costly (Hayden et al., 2018). Many researchers have focused their attention on predicting the residual frictional angle from the available indexes, like the Atterberg limits, or the clay or sand fraction. Among all the available indexes, the correlations based on the Atterberg limits, including the liquid limit, the plastic limit, and the plasticity index, appear as attractive alternatives in laboratory shear tests in practice. Some literature (Mesti and Cepeda-Diaz, 1986; Stark et al., 2005; Wen et al., 2007; Hayden et al., 2018; Fang et al., 2019) focused on illustrating the relationship between the residual frictional angle and the liquid limit. Some literature (Voight, 1973; Seyeek, 1978; Wen et al., 2007; Fang et al., 2019) focused on illustrating the relationship between the residual frictional angle and the plastic limit. And other literature (De, 1973; Mesti and Shahien, 2003; Fang et al., 2019) focused on illustrating the relationship between the residual frictional angle and the plasticity index. Fang et al. (2019) conducted a study on finding the relationship between the residual strength and the Atterberg limits for reservoir embankment soils. They pointed out that the liquid limit has a better relationship with the residual strength than the plastic limit or the plasticity index. On the other hand, some authors (Lupini, 1981; Wesley, 2003 and Hayden et al., 2018) emphasized that the relationships between the residual frictional angle and the soil index properties could not be uniform due to the great diversity among the types and origins of natural soils, but that such correlations could be of value for specific types and origins of soils, which implies that research focusing on the prediction of the residual strength for the same types of soils is worthwhile.

9. Conclusion

The present study attempted to review the main influencing factors of the residual strength in the test conditions and the possible indexes in order to predict the residual strength of soils. Based on the above efforts, the following general conclusions are drawn:
1. Due to its simplicity and availability, the ring shear apparatus is recommended instead of the direct shear box. With the demands of social development, ring shear apparatuses which can simulate the complex geological conditions during earthquakes and under groundwater fluctuations have been developed.
2. To decrease the effect of normal stress on the residual strength, high normal stress is recommended for use in the tests. The nonlinear phenomenon in the shear strength envelope is due to the low degree of orientation under the low normal stress.
3. The effect of overconsolidation on the residual strength can be ignored. In addition, to obtain the residual strength effectively, overconsolidation is recommended.
4. Three kinds of shear rate effects indicate that the residual strength is clearly affected by the shear rate. However, if the shear rate is less than 0.1 mm/min, the residual strength is dependent on the rate.
5. Although the effect of acceleration on the residual strength can be ignored under small absolute values of acceleration, more researches on a wider range of acceleration values and on different kinds of soils would be beneficial, as only a few researches have focused on this issue.
6. Predictions of the residual strength of soils have continued to be made for around 50 years, but a consistent and accurate theory has yet to be established. Among the available indexes, the liquid limit is a better available index than the plastic limit or the plasticity index for predicting the residual strength of soils.
Acknowledgments

The financial support of the Gifu University Rearing Program for Basin Water Environmental Leaders and the Ministry of Education, Culture, Sports, Science and Technology is gratefully acknowledged.

References

Ali J, Sheikh KA, Akhtar K, Khan AQ and Hussain M (2015) Stability analysis of slopes using numerical simulation based on finite element method and limiting equilibrium approach. Asian Acad. Res. J. Multidiscip., 2 (3): 371–379.

Bhat DR, Bhandary NP and Yatabe R (2013) Effect of shear rate on residual strength of Kaolin clay. Electron. J. Geotech. Eng., 18: 1387–1396.

Bhat DR and Yatabe R (2015) Effect of shear rate on residual strength of Kaolin clay. Electron. J. Geotech. Eng., 21 (2): 309–319.

Bishop AW (1955) The use of slip circles in the stability analysis of Earth slopes. Geotechnique, 5 (1): 7–17.

Bishop AW (1971) The influence of progressive failure on the method of stability analysis. Geotechnique, 21 (2): 309–319.

Bishop AW, Green GE, Garga VK, Andresen A and Brown JD (1971) A new ring shear apparatus and its application to measurement of residual strength. Geotechnique, 21 (4): 273–328.

Bromhead EN (1979) A simple ring shear apparatus. Ground Eng., 12 (5): 40–44.

Carrubba P and Colonna P (2006) Monotonic fast residual strength of clay soils. Italian Geotech. J., 3: 32–51.

Charles JA and Soares MM (1984) The stability of slopes in soils with nonlinear failure envelopes. Can. Geotech. J., 21 (3): 397–406.

Chen XP and Liu D (2014) Residual strength of slip zone soils. Landslides, 11 (2): 305–314.

Cullen RM and Donald IB (1971) Residual strength determination in direct shear. Proc. 1st Aust. N. Z. Conf. Geomech., 1: 1–10.

Dai FC, Wang SJ and Lee CF (1998) The drained residual strength of volcanics-derived soil sampled on Lantau Island, Hong Kong. J. Eng. Geol., 6 (3): 223–229 (in Chinese).

Day RW and Axten GW (1989) Surficial stability of compacted clay slopes. J. Geotech. Eng. ASCE, 115 (4): 577–580.

De PK and Furdas B (1973) Discussion –Correlation between Atterberg plasticity limits and residual shear strength of natural soils. Geotechnique, 23 (4): 600–601.

Duong NT, Suzuki M and Hai NV (2018) Rate and acceleration effects on residual strength of Kaolin and kaolin-bentonite mixtures in ring shearing. Soils Found., 58 (5): 1153–1172.

Eid HT, Rabie KH and Wijewickreme D (2016) Drained residual shear strength at effective normal stresses relevant to soil slope stability analyses. Eng. Geol., 204: 94–107.

Fang C, Shimizu H, Nishimura S, Hiroamatsu K, Onishi T and Nishiyama T (2018) Seismic risk evaluation of irrigation tanks: A case study in Ishigawa-Cho, Gifu Prefecture, Japan. Int. J. GEOMATE, 14 (41): 1–6.

Fang C, Shimizu H, Nishimura S and Nishiyama T (2019) Predicting the residual frictional angle by Atterberg limits for reservoir embankment soils. Int. J. GEOMATE, 17 (63): 111–118.

Fellenius W (1936) Calculation of the Stability of Earth Dams, Proc. 2nd Congr. Large Dams, 4: 445–463.

Fukuoka H and Sassa K (1991) High-speed high-stress ring shear tests on granular soils and clayey soils. Gen. Tech. Rep. PSW-GTR-130, USDA Forest Service: 33–41.

Garga VK and Sendano JI (2002) Steady state strength of sands in a constant volume ring-shear apparatus. Geotech. Test. J., 25 (4): 414–421.

Gazetas G, Garini E, Anastasopoulos I and Georgarakos T (2009) Effects of near-fault ground shaking on sliding systems. J. Geotech. Geoenviron. Eng., ASCE, 135(12): 1906–1920.

Gibo S, Egashira K and Ohshuto M (1987) Residual strength of smectite-dominated soils from the Kamenose landslide in Japan. Can. Geotech. J., 24: 456–461.

Gratchev IB and Sassa K (2015) Shear strength of clay at different shear rates. J. Geotech. Geoenviron. Eng. (ASCE), 141 (5): 06015002-6015011.

Hammouri NA, Hussein Malikawi AI, Yamin MMA (2008) Stability analysis of slopes using the finite element method and limiting equilibrium approach. Bull. Eng. Geol. Environ., 67 (4): 471–478.

Hawkins AB and Privett KD (1985) Measurement and use of residual shear strength of cohesive soils. Ground Eng., 18 (8): 22–29.

Hayden CP, Purchase-Sanborn K and Dewoolkar M (2018) Comparison of site-specific and empirical correlations for drained residual shear strength. Geotechnique, 68 (12): 1099–1108.
Hinton E and Irons BM (1968) Least squares smoothing of experimental data using finite elements. J. Br. Soc. Strain Meas., 14: 24-27.

Hong Y, Sun T, Luan MT, Zheng XY and Wang FW (2009) Development and application of geotechnical ring shear apparatus: an overview. Rock Soil Mech., 30 (3): 628–634 (in Chinese).

Hungr O and Morgenstern NR (1984) High velocity ring shear tests on sand. Geotechnique, 34(3): 415–421.

Hvorslev MJ (1939) Torsion shear tests and their place in the determination of the shearing resistance of soils. Proc. Am. Soc. Mater. 39: 999–1022.

Insley AE, Chatterji PK, and Smith LB (1977) Use of residual strength for stability analyses of embankment foundations containing preexisting failure surfaces. Can. Geotech. J., 14 (3): 408–428.

Inukai M (2008) Acceleration records in recent earthquakes and structural response values. 14th World Conf. Earthquake Eng., Beijing, China.

Janbu N (1954) Stability analysis of slopes with dimensionless parameters. Ph.D. Thesis, Harv. Univ.

Khosravi M, Meehan CL, Cacciola DV and Khosravi A (2013) Effect of fast shearing on the residual shear strengths measured along preexisting shear surfaces in Kaolinite. Geotech. Spec. Publ. 231: 245–254.

Kimura S, Nakamura S, Vithana SB and Sakai K (2013) Shear rate effect on residual strength of landslide soils in the slow rate range. Landslides 11 (6): 969–979.

Kjellman W (1951) Testing the shear strength of clay in Sweden. Geotechnique, 2 (3): 225–235.

Korzyck A (2016) Effect of the vertical seismic accelerations on the stability of earth dams. Arch. Hydro-Eng. Environ. Mech., 63(2-3): 101–120.

La Gatta DP (1970) Residual strength of clay and clay-shales by rotation shear tests. Ph.D. Thesis, Harv. Univ.

Lane P and Griffiths D (2000) Assessment of stability of slopes under drawdown conditions. J. Geotech. Geoenvion. Eng. (ASCE), 126(5): 443–450.

Li YR, Wen BP, Aydin A and Ju NP (2013) Ring shear tests on slip zone soils of three giant landslides in the three gorges project area. Eng. Geol., 154: 106–115.

Li DY, Yin KL, Glade T and Leo C (2017) Effect of over-consolidation and shear rate on the residual strength of soils of silty sand in the Three Gorges Reservoir. Sci. Rep. 7: 5503.

Lian BQ, Peng JB, Wang XG and Huang QB (2018) Influence of shear rate on the residual strength characteristic of three landslides soils in loess area. Nat. Hazards Earth Syst. Sci. Discuss.: 1–24.

Lupini JF, Skinner AE and Vaughan PR (1981) Drained residual strength of cohesive soils. Geotechnique, 31(2): 181–213.

Maksimovic M (1989) Nonlinear failure envelope for soils. J. Geotech. Eng. ASCE, 115 (4): 581–586.

Marcuson WF, Hynes ME and Franklin AG (1990) Evaluation and Use of Residual Strength in Seismic Safety Analysis of Embankments. Earthquake Spectra, 6 (3): 529–572.

Matsui T and San KC (1992) Finite element slope stability analysis by shear strength reduction technique. Soils Found., 32 (1): 59–70.

Mesri G and Cepeda-Diaz AF (1986) Residual shear strength of clays and shales. Geotechnique 36 (2): 269-274.

Mesri G and Shahien M (2003) Residual shear strength mobilized in first-time slope failures. J. Geotech. Geoenviron. Eng., 129 (1): 12-31.

Morgenstern NR and Price VE (1965) The Analysis of the Stability of General Slip Surfaces. Geotechnique, 15(1): 79–93.

Newmark NM (1965) Effects of earthquakes on dams and embankments. Geotechnique, 15 (2): 137–160.

Parathiras AN (1995) Displacement rate and shear direction effects on the residual strength of plastic soils. Proc. 7th Int. Conf. Soil Dyn. Earthquake Eng.: 67–72.

Penman A (1953) Shear characteristics of saturated silt measured in triaxial compression. Geotechnique, 3 (8): 312–328.

Ponce VM and Bell JM (1971) Shear strength of sand at extremely low pressures. J. Soil Mech. Found. Div. ASCE, 97 (4): 625–638.

Potts DM, Dounias GT and Vaughan PR (1990) Finite element analysis of progressive failure of Carsington embankment. Geotechnique, 40 (1): 79–102.

Saito R, Fukuoka H and Sassa K (2006) Experimental study on the rate effect on the shear strength. Disaster Mitigation of Debris Flows, Slope Failure Landslides: 421–427.

Sassa K (1997) A new intelligent-type dynamic-loading ring-shear apparatus. Landslide News 10: 33.
Sassa K, Fukuoka H, Wang G and Ishikawa N (2004) Undrained dynamic-loading ring-shear apparatus and its application to landslide dynamics, Landslides 1: 7–19.

Scaringi G and Di Maio C (2016) Influence of displacement rate on residual shear strength of clays. Procedia Earth Planet. Sci., 16: 137–145.

Seyeek J (1978) Residual shear strength of soils. Bull. Eng. Geol. Environ., 17 (1): 73–75.

Skempton AW (1964) Long-term stability of clay slopes. Geotechnique, 14 (2): 77–102.

Skempton, AW (1985) Residual strength of clays in landslides, folded strata and the laboratory. Geotechnique, 35 (1): 3–18.

So EK and Okada F (1978) Some factors influencing the residual strength of remoulded clays. Soils Found., 18 (4): 107–118 (in Japanese).

Stark TD, Choi H and McCone S (2005) Drained shear strength parameters for analysis of landslides. J. Geotech. Geoenviron. Eng., ASCE, 131(5): 575–588.

Stark TD and Vettel JJ (1992) Bromhead ring shear test procedure. Geotech. Test. J., 15 (1): 24–32.

Suzuki M (1998) Basic study on residual strength of soil by ring shear test. Ph.D. Thesis, Shinshu Univ. (in Japanese).

Suzuki M, Hai NV and Yamamoto T (2017) Ring shear characteristics of discontinuous plane. Soils Found., 57 (1): 1–22.

Suzuki M, Tsuzuki S and Yamamoto T (2007) Residual strength characteristics of naturally and artificially cemented clays in reversal direct box shear test. Soils Found., 47 (6): 1029–1044.

Tika TM (1989) The effect of rate of shear on the residual strength of soil. Ph.D. Thesis, Univ. London.

Tika TE and Hutchison JN (1999) Ring shear tests on soil from the Vaiont landslide slip surface. Geotechnique, 49 (1): 59–74.

Tika TE, Vaughan PR and Lemos LJJ (1996) Fast shearing of preexisting shear zones in soils. Geotechnique, 46 (2): 197–233.

Tiwari B and Marui H (2005) A new method for the correlation of residual shear strength of the soil with mineralogical composition. J. Geotech. Geoenviron. Eng., ASCE, 131 (9): 1139–1150.

Townsend FC and Gilbert PA (1973) Tests to measure residual strength of some clay shales. Geotechnique, 23 (2): 267–271.

Vithana SB, Nakamura S, Kimura S and Gibo S (2012) Effects of overconsolidation ratios on the shear strength of remoulded slip surface soils in ring shear. Eng Geol., 131–132: 29–36.

Voight B (1973) Correlation between Atterberg plasticity limits and residual shear strength of natural soil. Geotechnique, 23 (2): 265–267.

Wang YC and Cong L (2019) Effects of water content and shearing rate on residual shear stress. Arab. J. Sci. Eng. 1–15.

Wen BP, Aydin A, Duzgoren-Aydin NS, Li YR, Chen YR and Xiao SD (2007) Residual strength of slip zones of large landslides in the Three Gorges area, China. Eng. Geol., 93 (3–4): 82–98.

Wesley LD (2003) Residual strength of clay and correlations using Atterberg limits. Geotechnique, 53 (7): 669–672.

Xu Q, Yuan Y, Zeng YP and Hack R (2011) Some new pre-warning criteria for creep slope failure. Sci. China: Technol. Sci., 54: 210–220.

Yuan WN, Fan W, Jiang CC and Peng XL (2019) Experimental study on the shear behaviors of loess and paleosol based on ring shear tests. Eng. Geol., 250:11–20.