RESIDUAL SHEAR STRENGTH OF SOIL AND ITS SHEAR DISPLACEMENT RATE DEPENDENCY: AN OVERVIEW

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Abstract: Residual strength of soil plays an important role in slope stability analysis of reactivated landslides or slopes that contain a pre-existing shear surface. This parameter depends not only on the physical properties of the soil, but also on shear displacement rate and other testing conditions. The paper aims to review the shear rate dependency of residual strength and the residual interface strength between bi-materials. In addition, the methods of determination of residual strength and its application to slope stability analysis are also reported. The literature review shows that the shear displacement rate affects the residual strength to some extent, especially at a fast shear rate. It is also recommended that the reasons for the rate dependency of residual strength should be further examined. In addition, with regard to the change in shear velocity, the effect of acceleration change on residual strength has not yet been studied. The behaviour of residual interface strength is similar to that of the soil. Nevertheless, the behaviour of residual strength at the boundary between two soil layers having different physical properties (e.g. plasticity and permeability) requires further investigation.

Keywords: rate dependency; residual interface strength; first-time slides; strength recovery.

1. Introduction

Residual shear strength has been investigated since the 1930s (Skempton, 1964). However, the significance of residual shear strength became considerably more evident after the 4th Rankine Lecture of Skempton (1964). In this lecture, the residual shear strength was defined as the minimum drained shear strength, at which the soil undergone a large shear displacement under the given effective normal stress.

The residual strength plays an important role in evaluating and predicting the stability of slopes that contain a pre-existing shear surface or comprise stiff and fissured clay. The residual strength mainly depends on the physical properties (plasticity characteristics), size and shape of particles, mineralogical compositions, and pore water chemistry. It also depends on testing conditions, such as normal stress and shear displacement rates. However, the residual strength is mostly independent of the stress history (overconsolidation ratio: OCR), the initial water content, the initial void ratio, and sample preparation. The factors affecting the residual strength have been extensively investigated in the literature. Nevertheless, the effects of some other factors (e.g., shear displacement rate) on the residual strength are still in doubt.

The main objectives of this study are to review the shear rate dependency of residual strength and the behaviour of residual interface strength between bi-materials. In addition, reliable methods used to determine the residual strength and the application of residual strength to slope stability analysis are reviewed.

2. Determination of residual strength of soil

The residual strength can be obtained by various laboratory testing methods, such as the triaxial shear test on precut specimen (TS), reversal direct box shear test (RDBST), and ring shear test (RST). In the RDBST and RST, a large shear displacement on the shear surface must be reached to obtain the residual state of soil when subjected to shear stresses.

The main differences between the three basic methods are the amount of shear displacement that can be accumulated in each method. In the TS, the amount of axial strain is limited of about 15% of the 100 mm-height of the sample (axial displacement ~15 mm). This deformation cannot represent the true residual state. However, the orientation of particles isn't changed during shearing. Thus, if the sample is precut and polished to orient the particles on the shear surface, the residual shear strength can be achieved by this method. Nevertheless, using the TS on the precut specimen to determine the residual strength still results in uncertainty (Chen and Liu, 2014). In the RDBST, the amount of horizontal displacement in one cycle is about 6–7 mm, and the shear displacement can reach the residual state by reversing the direction of shearing (about five cycles or more). However, reversing the shear direction (upward and backward) may disturb the orientation of particles on the shear surface. Different from TS and RDBST methods, the unlimited displacement can be obtained in one direction in the RS so that the orientation of grains on the shear surface is not changed during shearing, and a good preferred orientation of grains can be achieved. Therefore, the RS can yield a residual strength that is in good agreement with the field value. Table 1 shows the test result of the residual strength of some clays obtained from different testing methods. It can be seen that the residual strength (expressed in term of friction angle) of all clays obtained from RST is the lowest values.

Tab. 1. Residual friction angles of some clays obtained from different testing methods

Soils	Type of sample	Test methods	Average, ϕ_r (deg), c_r=0	References
Blue London clay (Wraybury)	Undisturbed, w_L=70%; PI=29%; CF=58%.	RDBST	13.5^0	Bishop et al. (1971)
	Undisturbed, w_L=72%; PI=29%; CF=57%.	Drained TS, presheared to large displacement	10.5^0	
		RST (Bishop's type)	9.4^0	
	Remoulded, w_L =72%; PI=29%; CF=57%.	RST (Bishop's type) (one sample)	9.5^0	
	Undisturbed, W_L=71.5%; PI=22.4%.	RST (Bishop's type)	9.3^0	La Gatta (1970)
	Remoulded, w_L=71.5%; PI=22.4%.	RST (Bishop's type)	8.3^0	
Brown London clay (Walthamstow)	Slip surface, w_L =43-76%; PI=22-46%; CF=40-65%.	Drained, direct shear test	14.0^0	Bishop et al. (1971)
	Undisturbed, cut-plane w_L=70%; PI=26%; CF=50%.	Drained, direct shear test	14.2^0	
	Slip surface, w_L=71%; PI=26%; CF=63%.	Drained TS	13.7^0	
	Undisturbed, w_L=66%; PI=24%	RST (Bishop's type)	10.0^0	
	Remoulded, w_L=66%; PI=24%	RST (Bishop's type)	9.7^0	
Blue London clay (Herne Bay)	Undisturbed, w_L=81%; PI=33%; CF=61%.	RDBBST	13.5^0	
	Remoulded, w_L=85%; PI=34%; CF=59%.	RDBST	12.5^0	
	Undisturbed, cut-plane w_L=81%; PI=33%; CF=61%	Drained TS	14.7^0	
	Over-consolidated, w_L=95%; PI=61%; CF=59%	RST (Bishop's type)	9.4^0	

Ring shear apparatus have been widely developed and used to determine the residual shear strength for many years. The RST was first used to investigate the residual strength of undisturbed clays and of clays consolidated from slurry conditions in the 1930s (Skempton, 1964). However, the use of ring shear apparatus to investigate residual strength was substaintially developed after the 4th Rankine Lecture (Skempton, 1964). In general, there are two original versions, one was developed based on the principles of the Imperial College–Norwegian Geotechnical Institute (Bishop's type) (Bishop et al., 1971), and the other on the Bromhead ring shear device (Bromhead's type) (Bromhead, 1979). The main difference between the two these types is in the location of the shear plane. In Bishop's type, the shear plane is taken place at the midheight of the specimen, whereas in the Bromhead's type, the shear zone is at the top of the specimen. Both these types of ring shear apparatus have been modified and improved from their original designs. The Bromhead's type was modified by Stark and Eid (1993), Stark and Poeppel (1994), Stark and Contreras (1996), Sedano et al. (2007), Meehan et al. (2007, 2008), and Merchan et al. (2011), and the Bishop's type was developed by Sassa (1984), Hungr and Morgenstren (1984), Tika et al. (1996), and Suzuki et al. (1997). Sadrekarimi and Olson (2009) also have developed a new ring shear apparatus based on the Bromhead's type. However, in this device, the shear zone is located at the bottom of the specimen.

In recent, two types of ring shear apparatus, as mentioned above, have often been widely employed to determine the residual strength of soil. However, each type of device exhibits its own advantages and disadvantages. In the Bromhead's type, the magnitude of the wall friction along the inner and outer circumferences of the specimen is one of the main factors affecting the residual strength. The wall friction increases with increasing settlement of the top porous stones, consequently results in an increase in residual strength. In addition, some soils may be extruded during shearing and trapped between the top planes and the shear box. This phenomenon also brings about an increase in shearing resistance (Stark and Vettel, 1992). To minimise the settlement of the top porous stone, Stark and Vettel (1992) proposed the 'flush' test procedure in which the remoulded soil is added and reconsolidated to ensure that the porous stone is approximately flush with the container before being sheared. However, the flush test procedure does not apply for the multistage procedure. Hence, Stark (1995) suggested the multistage test procedure using a modified Bromhead device (Stark and Eid, 1993) and overconsolidated, precut, remoulded samples to measure the residual shear strength of a pre-existing slip surface.

In the determination of residual strength of soils using a Bishop-type ring shear apparatus (Bishop et al., 1971), the normal stress, the frictional force (F), and the gap between upper and lower rings might affect the test results. The testing conditions may be either stress or strain controlled. To obtain the residual strength in ring shearing, the strain-controlled method is often executed, i.e. displacement rate and normal stress are severally controlled, and shear stress is measured. The frictional force is induced by the relative displacement of the specimen to the shear box, which develops between the specimen and the inner perimeter of the shear box. It acts upward in the case of specimen contraction and downward in the case of specimen dilation (Fig. 1). The net normal stress is calculated by subtracting the measured frictional force. With regard to the gap, it is closed during consolidation to prevent soil from being leaked and kept opening during shearing to mitigate the contact friction between the halves of the shear box. However, during shearing, some soil particles might leak out through the gap between the upper and lower ring of the shear box. The amount of soil leakage depends on the magnitude of the gap and then affects the measured shear strength. Suzuki (2008) investigated the effect of the gap (d) on the measured shear strength in the RS (Fig. 2). This figure shows that the gap significantly affects the measured shear strength of Ube Masado (weathered granite soils) and Toyoura sand. Nevertheless, the ratio (d/D_{50}) of about 5 to 10 has a little effect on the test results. Therefore, it is important to measure the frictional force (*F*) and design a suitable gap (*d*) to obtain an accurate value of shear strength.

Briefly, the wall friction and the soil extrusion are the two main factors affecting the residual strength value in both Bromhead- and Bishop-type ring shear apparatus. The Bromhead-type apparatus is quite straightforward (in term of technique and its system), and less expensive than Bishop's type. However, in Bromhead's type, the shear surface is located at the boundary between the loading platen and specimen, which may not reflect the actual contact in landslides. In addition, the wall friction is not measured in Bromhead's type, and it may cause an error in test results. By contrast, the slip surface in Bishop's type is at the soil–soil contact, and the frictional force is measured to calculate the net normal stress.

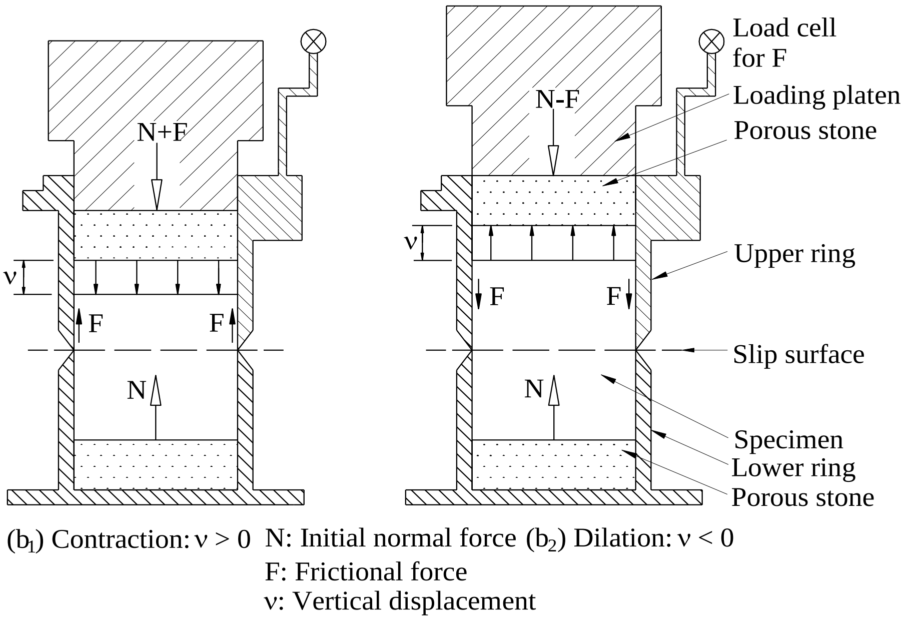

Fig. 1. System for measuring friction force and controlling normal force (Suzuki et al., 1997)

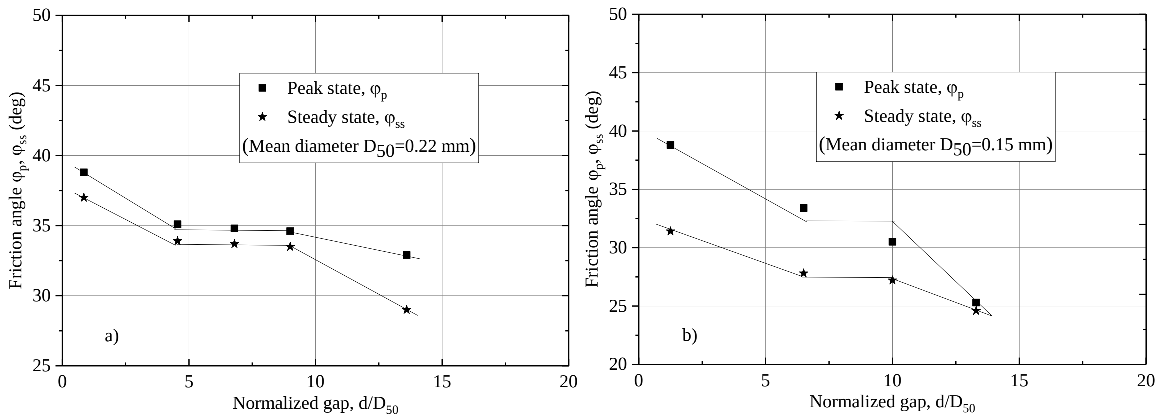

Fig. 2. Relation between normalised gap and internal friction angle for (a) Ube Masado soil and (b) Toyoura sand (Suzuki, 2008).

Although the RST may yield an accurate value of residual strength, it is expensive and difficult to prepare annular specimens. In some cases, the precut specimens (specimens for which a failure surface exists) can be used to determine the residual strength of soils using RDBST (Townsend and Gilbert, 1976; Chowdhury and Bertoldi, 1977; Askarani and Pakbaz, 2015). To reduce the test duration in determining residual strength, a multistage procedure (increasing or decreasing the effective normal stress) can be employed in the ring shear apparatus or reversal direct shear test with precut specimens (e.g. Anderson and Hammoud, 1988; Stark and Vettel, 1992; Stark, 1995; Tiwari and Marui, 2004, 2005).

The hyperbolic approximation method was applied to determine the residual shear strength from the test results. In this method, the relationship between, $\theta/(\tau/\sigma_N)$, and shear displacement angle, θ was plotted ($\theta>\theta_p$ with θ_p is the shear displacement angle at the peak stress). Hyperbolic approximation parameters, *a* and *b*, are given by the segment, and the gradient of the straight line are fitted to the measurement of the relationship between $\theta/(\tau/\sigma_N)$ and θ by the least square method. If the approximated hyperbola is in good agreement with the measurement, $(\tau/\sigma_N)_r$ is given as the inverse of *b*. The validity of the data fitting can be assessed using the correlation coefficient, R^2 (Fig. 3) The application of this method was based on the test results of kaolin and natural clays under various test conditions (Suzuki et al., 1997).

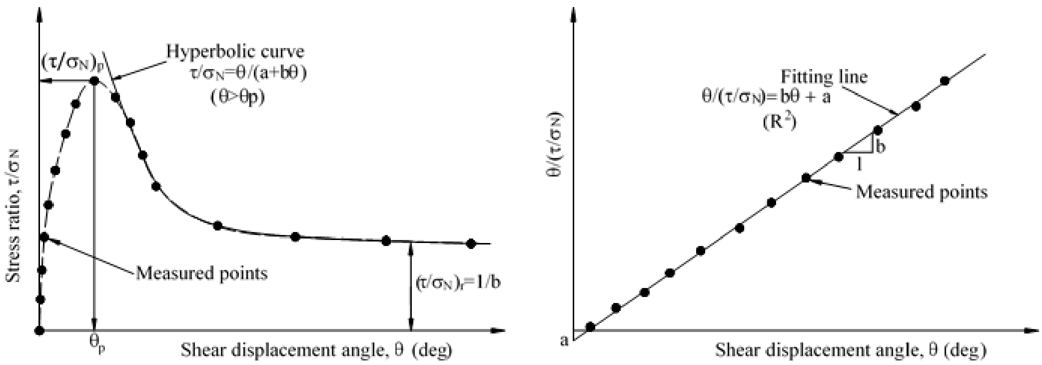

Fig. 3. Schematic diagram for determining the residual strength by a hyperbolic curve approximation method (Suzuki et al., 1997)

3. Shear rate dependency of residual strength

A better understanding of the shear rate effect on the residual strength of a soil would be beneficial for predicting and evaluating the behaviour of reactivated landslides. Tika and Hutchinson (1999) suggested that catastrophic landslides at the Vaiont Dam occurred because of a negative rate effect. Accordingly, the fast residual strength was reduced to approximately 60% of the slow residual strength when the shear displacement rate exceeded 100 mm/min. Conversely, Leroueil (2001) and Wang et al. (2010) reported that a positive rate effect could avoid catastrophic landslides, even when a large shear displacement occurred in a short period of time. This is because of the positive rate effect, which might increase the residual strength as the shear displacement rate increases, resulting in an increase in stability of slopes. Moreover, rate effects play a significant role in the application of laboratory testing methods and test results. Therefore, numerous studies have examined the rate dependency of the residual strength of various soils. Differences in clay contents and particle shapes lead to different shear modes, resulting in different rate effects (Lupini et al., 1981; Skempton, 1985; Tika et al., 1996) (Fig. 4). In general, three possible rate effects – positive, neutral, and negative – have been studied in the literature (Fig. 5). It can be said that the rate dependency of residual strength may not be generalised.

Some causes of the rate effect have been proposed to explain the rate dependency of residual strength. A positive rate effect can be attributed to a change from sliding to turbulent shear mode (e.g. Skempton, 1985; Tika et al., 1996; Lemos, 2003; Bhat, 2013), the shear viscosity effect (Tika et al., 1996; Lemos, 2003; Carrubba and Colonna, 2006), and the crushing of round particles (Fukuoka and Sassa, 1991). On the contrary, a reduction in fast residual strength can be caused by the delayed dissipation of excess pore water pressure (e.g. Skempton, 1985; Parathias, 1995a, b; Petley and Taylor, 1999; Li et al., 2013).

It is noted that the excess pore water pressure may not affect the residual shear strength when a soil specimen is sheared at slow rates (e.g. Saito et al., 2006, 2007; Wang et al., 2010; Bhat, 2013; Kimura et al., 2013) or in sand or silty sand (Wang et al., 2010; Li et al., 2017). An increase in the porosity (void ratio) and water content in the shear zone also reduces the fast residual strength (Tika et al., 1996; Li et al., 2017), as does an increase in finer particles in the shear zone, as larger particles are pushed out of the shear zone (Saito et al., 2007; Li et al., 2017) or angular particles are crushed (Fukuoka and Sassa, 1991). Furthermore, the negative rate effect can be attributed to the testing conditions. Tika et al. (1996) stated that the penetration of free water from the water bath into the shear zone can accelerate the reduction of the residual shear strength. More recently, Gratchev and Sassa (2015) suggested that small rates of broken bond recovery and particle rebound at fast shear rates may reduce the residual strength.

Although the factors related to the rate effect have been extensively studied, there is still no consistent theory that precisely describes the rate effect on residual strength. This may be due to the differences in the test conditions and types of soil used in the various studies. The rate effect may also depend on the design of the apparatus and test procedure (Bromhead, 2004). In addition, the magnitude of the rate effect on residual strength may be influenced by the effective normal stress (e.g. Carrubba and Colonna, 2006; Kimura et al., 2013; Gratchev and Sassa, 2015), the clay fraction, the plasticity index (Suzuki et al., 2001, 2009), the soil density (Li and Aylin, 2013), and the pore water chemistry (Scaringi and Di Maio, 2016). Therefore, the reasons for the rate effect on the residual strength of soils should be further investigated.

In a creep landslide at residual state, the velocity or shear displacement rate of a landslide block is not always constant. The irregular change in velocity leads to a change in the acceleration, which may affect the residual strength (this is known as the acceleration effect). Although the rate effect is a basic factor affecting the stability of old landslides, changes in acceleration should be considered in the analysis. However, reliable information on how the acceleration effect influences the residual strength is not available

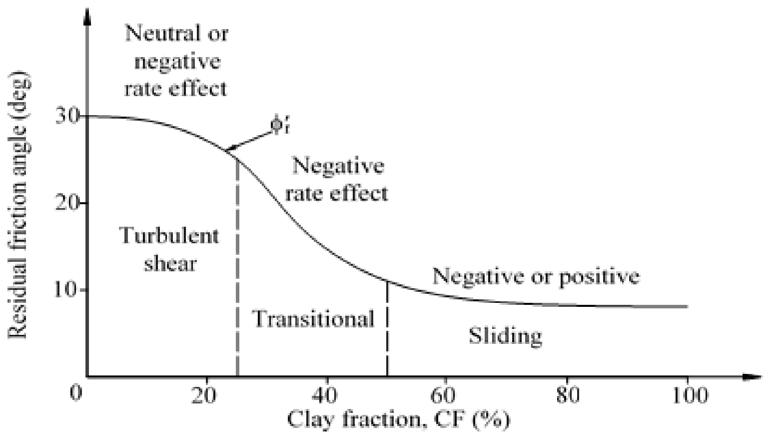

Fig. 4. Clay fraction, shear modes and rate effect relationship (after Lupini et al., 1981; Skempton, 1985; Tika et al., 1996).

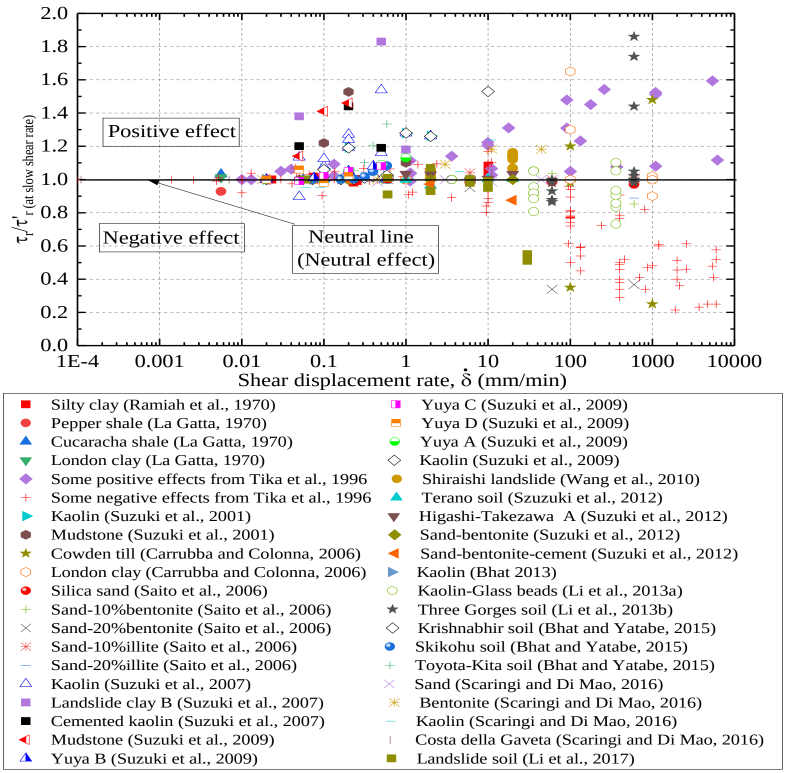

Fig. 5. Rate effect on the residual strength of different soil

4. Residual interface strength

The residual strength at the interface between bi-materials has been received much attention from the literature. The residual interface strength between soils and solid materials or between solid and solid materials (steel, concrete, geotextiles, geomembranes) relating to the stability of friction piles, retaining walls, anchor rods, earth reinforcement, offshore pipelines, and landfill cover has been studied extensively. In general, the residual interface strength is similar to the residual strength of the soil itself. It also depends on the properties of soils, size and shape of particles, applied normal stress and shear displacement rate. However, unlike the residual strength of the soil, the residual interface strength depends on the interface characteristics and the surface roughness of solid materials (Lemos and Vaughan, 2000).

In a landslide, the shear zone develops not only within the soil mass of one layer but also along the bedding plane, discontinuous plane or the interface between two soil layers (e.g. Bromhead and Ibsen, 2004; Tiwari et al., 2005; Sassa et al., 2005; Chigira and Yagi, 2006; Wang et al., 2007; Bromhead, 2013; Has and Nozaki, 2014). Bromhead and Ibsen (2004) described numerous landslides that occurred in sedimentary rocks on the coastline of Southeast Britain. These landslides are referred to the bedding-controlled landslides with rotational and transitional forms. The bedding-controlled landslides are the main types of instability along the southeast coastline of Britain. Chigira and Yagi (2006) and Wang et al. (2007) also reported that most of the landslides triggered by the 2004 Mid-Niigata-Prefecture earthquake occurred along the planar bedding. The planar-bedding-parallel-sliding surfaces were formed between sandstone and siltstone or between weathered and unweathered rocks. Has and Nozaki (2014) investigated the role of geological structure in landslides triggered by the 2007 Mid-Niigata offshore earthquake. These authors indicated that the bedding plane plays an important role in landslides. The slopes comprise sandstone and siltstone are easily sheared off along the bedding planes. Therefore, the residual strength at the interface between two layers should be considered in evaluating and predicting the slope stability.

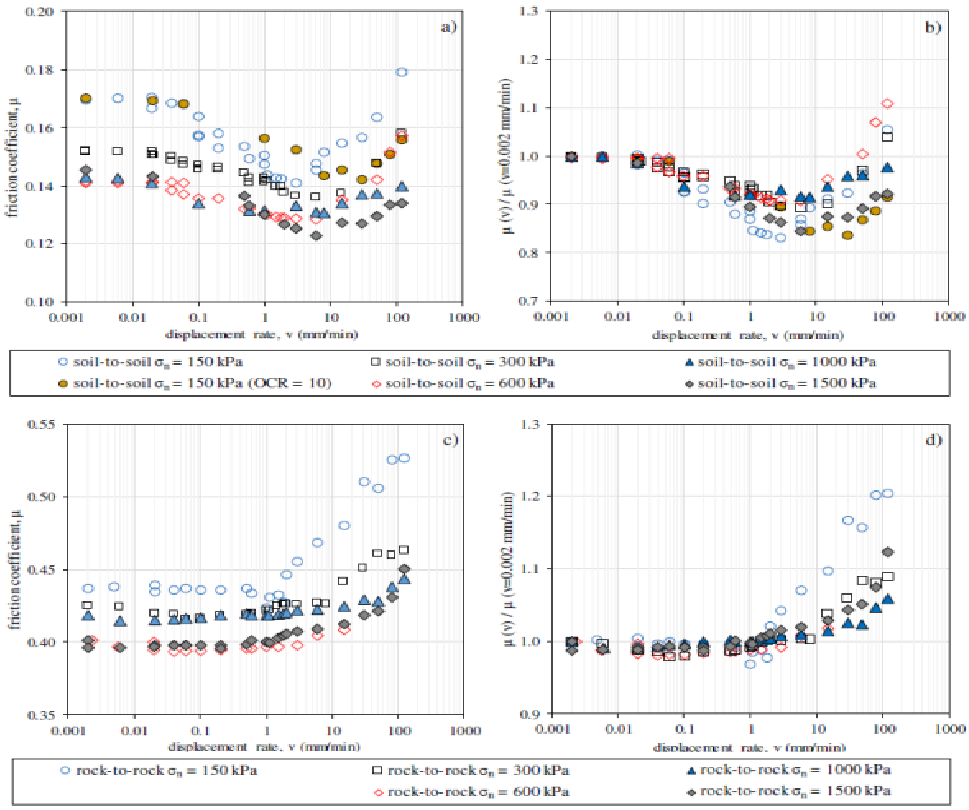

Fig. 6. Relationship between residual friction coefficient at the interface and shear displacement rate (Scaringi et al., 2017)

Recently, some studies have been conducted to examine the residual strength at the interface between two soil layers. Suzuki et al. (2017) conducted the RST on the samples composed of two halves to investigate the residual interface strength between two layers with different degrees of cementation (different cement content). The test results showed that the rate effect on residual strength also occurred in discontinuous planes. Scaringi et al. (2017) investigated the rate dependency of residual strength at the interface of soil to soil, rock to rock, and soil to rock at landslide stress level (Fig. 6). The test results showed that all sample assemblies exhibited a positive rate dependency of residual strength. However, depending on the materials in contact, the normal stress, and the stress history (OCR), the rate dependency of residual strength is different from each other. The investigations of Suzuki et al. (2017) and Scaringi et al. (2017) partly reflected the behaviour of residual strength on the boundary between two soil layers and the effects of some factors, such as stiffness, normal stress, shear displacement rates, and stress history. However, the behaviour of residual strength between two soil layers with different physical properties (plasticity, permeability) should be further examined.

5. Application of residual strength in slope stability analysis

In general, the residual state mostly exists in old landslides that have undergone a large shear displacement. However, the residual state may be present in bedding shears in folded strata, sheared joints or faults, an embankment failure, or stratigraphic discontinuities (weathered and unweathered; soft and stiff layer) (Skempton, 1985; Mesri and Shahien, 2003). In addition, the residual state may exist in first-time slides in clay fills and cutting slopes in fissured clays or a part of progressive failure (Mersi and Shahien, 2003). In these cases, although the slopes have undergone a small shear displacement, the shear strength becomes closer to the residual value. Therefore, the residual strength can be applied to reactivated landslides (post failure) or first-time failures in some specific cases, as mentioned above.

At the residual state, the experimental results show that the residual cohesion may be different from zero (Fig 7) (Tiwari and Marui, 2005). However, this value is insignificant. In addition, Skempton (1985) noted that the residual cohesion can be very low. Therefore, Stark et al. (2005) suggested that, at the residual state, the cohesion value should be zero in the stability analyses except for the result of back-analysis, which shows a value of cohesion greater than zero.

In some cases, the shear strength on the pre-existing shear surface may increase with elapsed time after failure because of the reconsolidation and the ageing or healing processes, especially at effective normal stresses of 100 kPa or less (Fig 8) (Stark and Hussain, 2010). However, it decreases to the residual strength value after a small shear displacement (Gibo et al., 2002; Stark et al., 2005; Stark and Hussain, 2010; Bhat et al., 2013a, b). Therefore, the shear strength recovery is not recommended for the design and repair of pre-existing shear surface slopes (Stark and Hussain, 2010).

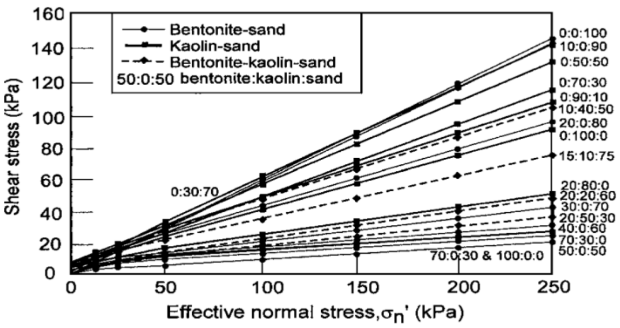

Fig. 7. Residual shear envelope for mixture samples (Tiwari and Marui, 2005).

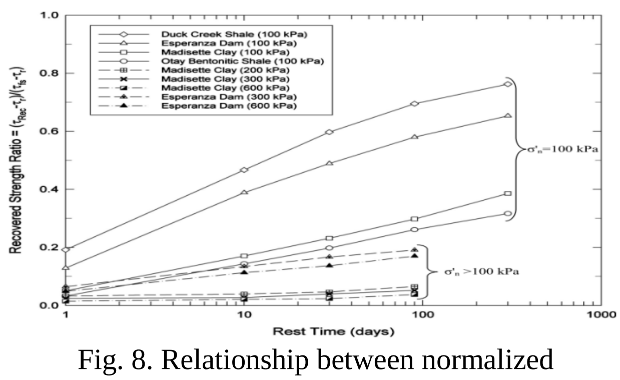

Fig. 8. Relationship between normalized strength ratio and the rest time (Stark and Hussain, 2010)

6. Conclusions

From the literature review conducted, some main conclusions are withdrawn as follows:

1.The RST is the most suitable method for determining the residual strength. However, the RDBST and precut specimens can be used to determine the residual strength. The multistage procedure (increasing or decreasing normal stress) is useful for determining the residual strength to reduce the testing duration.

2.The residual strength may depend on the shear displacement rates. However, a consistent theory for the rate dependency of residual strength has not been established. Therefore, it requires a further examination. In addition, regarding the change in shear rate, the acceleration effect on residual strength is still vague.

3.The residual interface strength plays a key role not only in the stability of friction piles, retaining walls, anchor rods, earth reinforcement, offshore pipelines, and landfill cover but also in the stability of slopes that contain bedding or discontinuous planes. The behaviour of the residual strength of the interface is similar to that of the soil itself. Nevertheless, the residual strength at the interface between two soil layers having different physical properties should be further studied.

4. The concept of residual state strength is applicable for reactivated landslides, first-time slides in stiff and fissured clays, embankment failures, and slopes having bedding or discontinuous planes. For some soils, residual state strength may recover after the reconsolidation and the aging or healing processes. However, it rapidly losses and reaches the residual value after a small shear displacement. Therefore, the residual strength recovery is not recommended for slope stability analysis.

References

[1] Anderson, W. F., Hammoud, F., 1988. Effective of testing procedure in ring shear tests, Geotech. Test. J. 11(3), 204-207.

[2] Askarani, K. K., Pakbaz, M. S., 2016. Drained shear strength of over-Consolidated compacted soil-cement. Journal of material in Cicil Engineering, ASCE 25(5).

[3] Bhat, D. R., 2013. Effect of shearing rate on residual strength of Kaolin clay. Electronic Journal of Geotechnical Engineering (EJGE) 18, 1387-1396
[4] Bhat, D. R., Bhandery, N. P., Yatabe, R., 2013a. Experimental study of strength recovery from residual strength on kaolin clay. International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering 7(1), 76–82.
[5] Bhat, D. R., Yatabe, R., 2015. Effect of shearing rate on residual strength of landslide soils. Engineering Geology for Society and Territory-Volume 2, 1211-1218.
[6] Bhat, D. R., Yatabe, R., Bhandary, N. P., 2013b. Study of preexisting shear surfaces of reactivated landslides from a strength recovery perspective. Journal of Asian Earth Sciences 77, 243–253.
[7] Bishop, A. W., Green, G. E., Garga, V. K., Anderson, A., Brown, J. D. ,1971. A new ring shear test apparatus and its application to the measurement of residual strength. Géotechnique 21(4), 273–328.
[8] Bromhead, E. N., 1979. A simple ring shear apparatus. Ground Engineering, 12(5), 40–44.
[9] Bromhead, E. N., 2004. Landslide slip surfaces: their origins, behavior and geometry. Landslides: Evaluation and Stabilization, Volume 1, 3–22.
[10] Bromhead, E. N., 2013. Reflections on the residual strength of clay soils, with special reference to bedding-controlled landslides. Quarterly Journal of Engineering Geology and Hydrogeology 46, 132–155.
[11] Bromhead, E. N., Ibsen, M, L., 2004. Bedding-controlled coastal landslides in Southeast Britan between Axmouth and the Thames Estuary. Landslides 1, 131-141.
[12] Carrubba, P., Colonna, P., 2006. Monotonic fast residual strength of clay soils. Italian Geotechnical Journal 3, 32-5.
[13] Chen, X. P., Liu, D., 2014. Residual strength of slip zone soils. Landslides 11, 305–314.
[14] Chigara, M., Yagi, H., 2006. Geological and geomorphological characteristics of landslides triggered by the 2000 Mid Niigata prefecture earthquake in Japan. Eng.Geol 82, 202–221.
[15] Chowdhury, R. N., Bertoldi, C., 1977. Residual shear tests on soil from two natural slopes. Australian Geomachanics Journal, 1-9.
[16] Fukuoka, H., Sassa, K., 1991. High-speed high-stress ring shear tests on granular soils and clayey soils. The XIX World congress of the International Union of Forestry Research Organizations, Canada, 33-41.
[17] Gibo, S., Egashura, K., Ohtsubo, M., Nakamura, S., 2002. Strength recovery from state in reactivated landslides. Géotechnique 52(9), 683–686.
[18] Gratchev, I., Sassa, K., 2015. Shear strength of clay at different shear rates, Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 141(5), 1–3.
[19] Gratchev, I., Sassa, K., Fukuoka, H., 2005. The shear strength of clayey soils from reactivated landslides. Annual of Disaster Prevention Research Institute, Kyoto, No 48.
[20] Has, B., Nozaki, T., 2014. Role of geological structure in the occurrence of earthquake-induced landslides, the case of the 2007 Mid–Niigata Offshore Earthquake, Japan. Eng.Geol 182, 25–36.
[21] Hungr, O., Morgenstern, N. R., 1984. High velocety ring shear tests on sand, Géotechnique 34(3), 415-421
[22] Kimura, S., Nakamura, S., Vithana, S. B., Sakai, K., 2013. Shearing rate effect on residual strength of landslide soils in the slow rate range. Landslides 11(6), 969–979.
[23] La Gatta D.P. 1970. Residual strength of clay and clay-shales by rotation shear tests. Harvard Soil Mechanics Series, No.86. Harvard University, Cambridge, Massachusetts.
[24] Lemos, L. J. L., 2003. Shear behavior of

pre-existing shear zones under fast loading – insights on the landslide motion. In Proceedings International Workshop on occurrence and mechanisms of flow-like landslides in natural slopes and earth fills, 229-236.
[25] Lemos, L. J. L., Vaughan, P. R., 2000. Clay-interface shear resistance. Geotechnique 50(1), 55-64.
[26] Leroueil, S., 2001. Natural slopes and cuts: movement and failure mechanisms. Géotechnique 51(3), 197–243.
[27] Li, D., Yin, K., Glade, T., Leo, C., 2017. Effect of over-consolidation and shear rate on the residual strength of soils of silty sand in the Three Gorges Reservoir. Scientific Reports 7, 1–11.
[28] Li, Y. R., Wen, B. P., Aydin, A. and Ju, N. P., 2013a. Ring shear tests on slip zone soils of three giant landslides in the three gorges project area. Engineering Geology 154, 106-115.
[29] Li, Y., Chan, L. S., Yeung, A. T., Xiang, X., 2013b. Effects of test conditions on shear behaviour of composite soil. Geotechnical Engineering, 1–11.
[30] Lupini, J. F., Skinner, A. E., Vaughan, P. G., 1981. The drained residual strength of cohesive soils. Géotechnique 31(2), 181–213.
[31] Meehan, C. L., Brandon, T. L., Duncan, J. M., 2007. Measuring drained residual strengths in the Bromhead ring shear. Geotechnical Testing Journal, 30(6).
[32] Meehan, C. L., Brandon, T. L., Duncan, J. M. 2008. Measuring fast shear strengths along slickensided surfaces in the Bromhead ring shear. Geotechnical Testing Journal 31(3).
[33] Merchan, V., Romero, E., Vaunat, J., 2011. An adpated ring shear apparatus for testing partly saturated soils in the high suction range. Geotech. Test. J. 34(5), 433-444.
[34] Mesri, G., Shahien, M., 2003. Residual shear strength mobilized in first time slope failures. J. Geotech. Geoenvironmental Engineering (ASCE), 129, 12–31.
[35] Parathias, A. N., 1995a. Displacement rate and shear direction effects on the residual strength of plastic soils. Proc 7th Int. Conference. Soil dynamics and Earthquake engineering, 67–72.
[36] Parathiras, A. N., 1995b. Effects of Earthquake induced rates of shearing on residual soil strength. Proceeding of 3rd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soils Dynamics, 1057–1060.
[37] Petley, D. J., Taylor, P., 1999. Modelling rapid shearing of cohesive soils along undulating shear surfaces. Proc. 7th Int. Symp. Slope stability engineering. Shikoku, Japan, Vol 1, 754–750.
[38] Ramiah, B. K., Dayalu, N. K., Purushothmarai, P., 1970. Influence of chemicals on residual strength of silty clay. Soil sand Foundations 10(1), 25-36.
[39] Sadrekarimi, A., Olson, M. S., 2009. A new ring shear device to measure the large displacement shearing behavior of sands. Geotechnical Testing Journal 32(3).
[40] Saito, R., Fukuoka, H. Sassa, K., 2006. Experimental study on the rate effect on the shear strength. Disaster Mitigation of Debris Flows, Slope Failures and Landslides, 421–427.
[41] Saito, R., Sassa, K. Fukuoka, H., 2006. Effect of shear rate on the internal friction angle of silica sand and bentonite mixture samples. Landslide–J. Jpn Landslide Society, 44 (1), 33–38 (in Japanese).
[42] Sassa, K., 1984. The mechanism staring liquefied landslides and debris flows. Proceeding of 4th International Symposium on Landslides, Torronto, 349-354.
[43] Sassa, K. Fukuoka, H. Wang, F., Wang, G., 2005. Dynamic properties of earthquake-induced large-scale rapid landslides within past landslide masses. Landslides 2, 125–134.
[44] Scaringi, G., Di Maio, C. 2016. Influence of displacement rate on residual shear strength of clays. Procedia Earth and Planetary Science 16, 137–145.

[45] Scaringi, G., Hu, W., Xu, Q., Huang, R., 2017. Shear-rate-dependent behavior of clayey bi-material interfaces at landslide stress levels. Geophysical Research Letters 44(23).

[46] Sedano, J. A. I., Vanapalli, S. K., Garga, V. K., 2007. Modified ring shear apparatus for unsaturated soils testing. Geotech. Test. J. 30(1), 39-47.

[47] Skempton, A.W., 1964. Long term stability of clay slopes. Géotechnique 14(2), 77–102.

[48] Skempton, A.W., 1985. Residual strength of clays in landslides, folded strata and the laboratory. Géotechnique 35(1), 3–18.

[49] Stark, T. D., Choi, H., Mccone, S., 2005. Drained shear strength parameters for analysis of landslides, J. Geotech. Geoenvironmental Engineering (ASCE), 131(5), 575–588.

[50] Stark, T. D., Contreras, I. A., 1996. Constant volume ring shear apparatus. Geotechnical Testing Journal 19(1), 3–11.

[51] Stark, T. D., Eid, H. T., 1993. Modified Bromhead ring shear apparatus. Geotechnical Testing Journal 16(1), 100–107.

[52] Stark, T. D., Hussain. M. 2010. Shear strength in preexisting landsides. J. Geotech. Geoenvironmental Engineering (ASCE), 136(7), 957–962.

[53] Stark, T. D., Poeppel, A. R., 1994. Landfill liner interface strengths from torsional-ring-shear tests. Journal of Geotechnical Engineering 120(3), 597-615

[54] Stark, T. D., Vettel, J. J., 1992. Bromhead ring shear test procedure. Geotechnical Testing Journal, 15, 24–32.

[55] Stark, T. D., 1995. Measurement of drained residual strength of overconsolidated clays. Transportation Research Record 1479, 26–34.

[56] Suzuki, M., 2008. 1.2. Shear strength of sands subjected to a large deformation in an earthquake and its rate effect, 17-46. Earthquake-induced Landslide Disasters in middle Mountains-Study Report on the 2004 Mid-Niigata Earthquake Part II-Geotechnical Engineering (in Japanese).

[57] Suzuki, M., Hai, N. V., Yamamoto, T., 2017. Ring shear characteristics of discontinuous plane. Soils and Founds 57(1), 1–22.

[58] Suzuki, M., Tanikawa, K., Fukuda, J. and Hisanaga, K., 2001. Variation in residual strength of clay with shearing speed, Memoir of the Faculty of Engineering of Yamaguchi Univ, 52(1), 45–49.

[59] Suzuki, M., Tsuzuki, S., Yamamoto, T., 2007. Residual strength characteristics of naturally and artifically cemented clays in reversal direct box shear test, Soils and Foundations 47(6), 1029-1044.

[60] Suzuki, M., Umezaki, T., Takahaza, H., 2012. Fast and cyclic shearing of cemented sand in Earthquake induced landslide. The Proceeding of 15th World Conference of Earthquake Engineering, Lisboa.

[61] Suzuki, M., Yamamoto, T., Kai, Y., 2009. Rate effect on residual state strength of clay related with fast landslide. Proc of International Symposium on Prediction and Simulation methods for Geohazard mitigation, 347–352.

[62] Suzuki, M., Umezaki, T., Kawakami, H., 1997. Relation between residual strength and shear displacement of clay in ring shear test. J. Jpn. Soc. Civ. Eng. 575 (III-40), 141–158 (in Japanese).

[63] Tika, T. E., Vaughan, P. R., Lemos, L. J. L., 1996. Fast shearing of pre-existing shear zones in soils. Géotechnique 46(2), 197–233.

[64] Tika, T. E., Hutchison, J. N., 1999. Ring shear tests on soil from the Vaiont landslide slip surface. Géotechnique 49(1), 59–74.

[65] Tiwari, B., Marui, H. 2004. Objective oriented multistage ring shear test for shear strength of landslide soil. J. Geotech. Geoenvironmental Engineering (ASCE), 130(2), 217–222.

[66] Tiwari, B. Brandon, T. L. Marui, H., Tuladhar, G. R., 2005. Comparison of residual shear strength from back analysis and ring shear tests on undrained and

remouled specimens. J. Geotech. Geoenvironmental Engineering, 131(9), 1071–1079.

[67] Tiwari, B., Marui, H., 2005. A new method for the correlation of residual shear strength of the soil with mineralogy composition. J. Geotech. Geoenvironmental Engineering, 131(9), 1139–1150.

[68] Townsend, F. C., Gilbert, P. A., 1976. Effects of specimen type on the residual strength of clays and clay shales. Soils specimen Preparation for Laboratory Testing, ASTM special technical publication 599, American Society for Testing and Materials, 43–65.

[69] Wang, G., Suemine, A., Schulz, W. H., 2010. Shear rate displacement strength control on the dynamics of rainfall-triggered landslides, Tokushima Prefecture, Japan. Earth Surface Process and Landforms 35(4), 407–416.

[70] Wang, H.B., Sassa, K., Xu, W. Y., 2007. Analysis of a spatial distribution of landslides triggered by the 2004 Chestsu earthquakes of Niigata Prefecture Japan. Nat Hazards 41, 43–60.