International Journal of GEOMATE, Nov., 2019 Vol.17, Issue 63, pp. 111 - 118
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2019.63.19131
Geotechnique, Construction Materials and Environment

PREDICTING RESIDUAL FRICTIONAL ANGLE BY ATTERBERG LIMITS FOR RESERVOIR EMBANKMENT SOILS

Chen Fang[1], Hideyoshi Shimizu[2], *Tatsuro Nishiyama[3], and Shin-Ichi Nishimura[3]

[1]The United Graduate School of Agricultural Science, Gifu University, Japan
[2]Emeritus Professor, Gifu University, Japan
[3]Faculty of Applied Biological Sciences, Gifu University, Japan

*Corresponding Author, Received: 01 March 2019, Revised: 24 March 2019, Accepted: 27 April 2019

ABSTRACT: Slope stability is one of the greatest issues of concern in geotechnical engineering. In slope stability analyses, the residual strength of slip zones is the most important parameter for evaluating slope stability and for understanding the reactivation mechanisms. However, it is time-consuming and costly to obtain the residual frictional angle through shear tests. This paper presents the results of a laboratory study designed to evaluate the correlations between the residual frictional angle and the Atterberg limits, which include the liquid limit, the plastic limit and the plasticity index, using eight kinds of reservoir embankment soil samples. The residual frictional angle was measured by the Bromhead ring shear apparatus using remolded samples. Based on the laboratory study, significant correlations between the residual frictional angle and the different indexes were proposed for the reservoir embankment soil, especially in terms of the particle size of the soil, which was less than 0.425 mm. Processing the data on the shear tests led to the discovery that the quantity of eight tests was sufficient for obtaining relevant accuracy in determining the residual frictional angle. Based on the results of the tests, the relationships between the residual frictional angle and all the indexes were found. Compared with the other indexes, the liquid limit had a better correlation with the residual frictional angle. Formulas were predicted in this study that can provide a convenient and highly accurate means for calculating the residual frictional angle value for application to worldwide geotechnical engineering projects.

Keywords: Residual frictional angle, Predicted formula, Liquid limit, Bromhead ring shear test

1. INTRODUCTION

Landslides are one of the Earth's most serious types of natural disasters. They cause the loss of human life and great damage to the social economy. Slope stability analyses are of boundless importance in geotechnical engineering, and the residual shear strength is a crucial parameter in slope stability analyses for the design of foundations for reservoir embankments, roads and other infrastructure projects, especially with regard to calculating the amount of settlement when considering the occurrence of large earthquakes [1-3].

The shear strength can be determined by laboratory tests. However, these tests are time-consuming and costly. Empirical correlations based on more readily available index properties, such as the Atterberg limits, appear as attractive alternatives in practice. Lupini [4] showed that the non-zero cohesion component in cohesive soils comes from low normal stress, rather than from the nature of these soils. Therefore, in this study, the residual strength of slip zones was examined in terms of the residual frictional angle. Many researchers have investigated the relationship between the residual frictional angle and different indexes. For example, some literature [5–8] has focused on finding the correlation between the residual frictional angle and the liquid limit; other literature [7, 9–10] has focused on finding the correlation between the residual frictional angle and the plastic limit. De [11] focused his study on finding the correlation between the residual frictional angle and the plasticity index. However, each correlation was different from the others. In [4, 8, 12], the authors stressed that the correlations between the residual frictional angle and the index properties of soils could not be general due to the great diversity among the types and origins of natural soils, but that such correlations could be valuable for specific types and origins of soils.

Moreover, it is noted that most of the existing correlations reported in literature have been derived for fine-grained particles (FGP) with few or none for coarse-grained particles (CGP) [13]. However, according to the Japanese Institute of Country-ology and Engineering, the desirable types of soil for use in reservoir embankments satisfy the following requirements: ① Good particle size distribution is necessary; ② Maximum size should be less than 10 ~ 15 cm; ③ The ratio of the fine-grained particles (FGP) (grain size of 0.075 mm or smaller) should be more than 15%; ④ The ratio of the FGP should be less than 50%. It is easy to find a higher amount of CGP in the composition of most embankment soil, which means that the formulas of prior researchers who focused on the correlations between the residual frictional angle and the Atterberg limits or other indexes cannot be applied to embankment soil with a higher amount of CGP.

The aim of this research is to point out the formulas for predicting the residual frictional angle by the Atterberg limits for reservoir embankment soil. The residual frictional angle can be obtained by the Bromhead ring shear apparatus. To find the correlations between the residual frictional angle and the Atterberg limits, basic physical property tests (liquid limit test, plastic limit test, compaction test, soil particle density test and a sieve analysis) were conducted on all the samples. According to the JIS A 1205 test guide, the size of each sample should be less than 0.425 mm in both the liquid limit and the plastic limit tests, implying that the soil taken from a practical reservoir embankment cannot be analyzed directly. However, Wen [7] pointed out that the residual strength is largely dependent on the clay content, and that the sand fraction has little influence on the residual strength of remolded soils. Li [14] also showed that the correlation between the residual strength and gravel is very weak. Therefore, there was little difference between the values for the residual frictional angles of the samples used in the Bromhead ring shear apparatus and the residual frictional angles of the practical samples taken from reservoir embankment soil. In other words, the formulas for predicting the residual frictional angle by the Atterberg limits in this research can be applied to practical reservoir embankment soil.

2. MATERIALS AND METHODOLOGY

2.1 Materials and sample preparation

It is said that the residual shear strength can be measured by testing remolded samples [15] and that the residual shear strength is not influenced by the stress history [5]. Therefore, remolded soil samples were used in this research. Samples were taken from Hojo, Matsuyama, Japan, as suitable material for reservoir embankments. Based on the basic theory of desirable soil for reservoir embankments, eight kinds of soil samples were made with a 0.075-mm sieve, as shown as Table 1. The grading curves of all the samples are shown in Fig. 1. The soil under 0.075 mm was analyzed as one whole part; therefore, the curves for the particle size distribution of the FGP were not shown here. It can be seen that all the samples have a good particle size distribution. The samples used in this research belong to the SF (fine-grained soil mixed sand) type according to the Standard for Soil Engineering Society JGS 0051-2009. Each sample was filtered through a 0.425-mm sieve because a grain size of more than 0.425 mm cannot be used in liquid limit or plastic limit tests according to the JIS A 1205 test guide. To precisely express the correlations between the residual frictional angle and the indexes, based on the percentage of each portion (fine-grained and coarse-grained particles) shown in Fig. 1, every new sample was created from a former sample, in 5-kg quantities (necessary for the compaction test), respectively, as shown as Table 2.

Table 1 Details on creating original samples for embankment soil

Samples	Ratio of FGP (%)	Every 1 kg of original soil
1	15.1	- 243g FGP
2	20.0	- 196g FGP
3	25.0	- 143g FGP
4	30.0	- 81g FGP
5	35.7	Original soil
6	40.0	+ 72g FGP
7	45.0	+ 169g FGP
8	49.5	+273g FGP

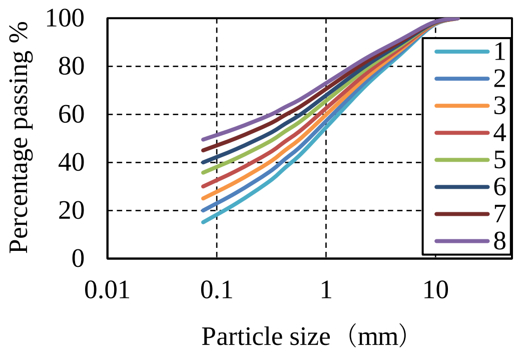

Fig. 1 Grading curves of all samples

Table 2 Samples used for plastic limit, liquid limit test and ring shear tests. Each sample was drawn from the sample shown in Fig. 1 based on the ratio of CGP and FGP. For example, Sample 1-1 was drawn from Sample 1.

Samples	CGP (%) 0.075-0.425mm	FGP (%) 0-0.075mm
1-1	60.01	39.99
2-1	51.62	48.38
3-1	44.46	55.54
4-1	38.38	61.62
5-1	32.42	67.58
6-1	28.58	71.42
7-1	24.59	75.41
8-1	21.40	78.60

2.2 Methodology

2.2.1 Measurement of physical properties

For the next step, tests were conducted on the prepared samples. The aim of the liquid limit test was to determine the moisture content at which the sample would begin to show the character of a flow object. The aim of the plastic limit test was to determine the moisture content limit at which the sample would have plastic character. Both tests were performed according to the JIS A 1205 test guide. Referring to the liquid limit and plastic limit values, the plasticity index was calculated based on the difference between them.

The aim of the compaction test was to determine the maximum dry density and the optimum moisture of the sample. A graph of the relationship between the dry density and the moisture content was drawn so as to obtain the maximum dry density and optimum moisture content. This test was performed based on the JIS A 1210 test guide.

The soil particle density test was based on the JIS A 1202 test guide. The results for each sample were used in the calculation of the compaction test.

The purpose of the sieve analysis was to determine the distribution of FGP and CGP by means of a sieve. Based on the JIS A 1205 test guide, each sample was passed through a 0.425-mm sieve as part of the Atterberg limits experiment. This sieve analysis was performed based on JIS A 1204.

2.2.2 Bromhead ring shear test

In laboratory tests, the shear strength is commonly determined by three main methods: the triaxial shear test, the direct shear box test and the ring shear test. The triaxial shear test is the most widely used shear strength test. It is known for its ability to control the drainage conditions and to measure the pore water pressure. However, when using the triaxial shear apparatus to determine the residual strength of the soil, there is a limit to the strain which can be applied to the specimen, especially for slip zone soils containing a certain amount of CGP [13]. Moreover, it is difficult to measure the residual strength of soil because the triaxial shear test cannot measure the strength along the sliding surface. Townsend and Gilbert [16] concluded that the residual shear strength values obtained from the direct shear box test and the ring shear test for remolded specimens are not significantly different. Compared with the direct shear box apparatus, the main advantage of the ring shear apparatus is that it shears the soil continuously in one direction for any magnitude of displacement. This allows for the full orientation of the particles parallel to the direction of shear and the development of a true residual strength condition. To determine the residual frictional angle, among the multiplicity of ring shear apparatuses reported by scientists [5, 17], the Bromhead ring shear apparatus is becoming widely used due to its simplicity of operation, its reasonable cost and its availability compared to previous models. Stark and Eid [18] also showed that the drained residual strength values measured with the Bromhead apparatus were in excellent agreement with the back-calculated values for landslides at Warden Point in the United Kingdom and at a site in Southern California.

In the Bromhead ring shear apparatus, an annual specimen of soil is used; it is 5 mm thick and has internal and external diameters of 70 mm and 100 mm, respectively. There are four main test procedures for measuring the drained residual strength of cohesive soils with the Bromhead ring shear apparatus: the single stage, pre-shearing, the multistage and the proposed “flush” procedure. Full descriptions of these procedures can be found in [19]. The results of the Bromhead ring shear tests by the multistage procedure are accurate, and this procedure can save more time than the other procedures [2]. The multistage procedure was used in this research to obtain the residual frictional angle.

Skempton [20] showed that the value of the residual strength acquired from laboratory tests is almost the same whether through the condition of normal consolidation or over consolidation, but that the time required to obtain the residual strength by normal consolidation is much longer than that by over consolidation. Based on this finding, the condition of over consolidation was applied in the present study for preparing the samples before shearing. The value of the pre-consolidation pressure was calculated by the weight of a 10-m-high embankment, equal to nearly 200 kPa. Therefore, the stress of 270 kPa was used as the over consolidation for the pre-consolidation pressure. So and Okada [21] also showed that the residual strength is independent of the over consolidation ratio from 1 to 100, which implied that 270 kPa of pressure used for over consolidation is proper in this research. To understand the situation of the samples during shearing in the Bromhead ring shear apparatus, the moisture content and the dry density were determined.

Scaringi [22] pointed out that the residual strength is independent of the displacement rate in the range of 10^{-6}-10^{-1} mm/min. Therefore, the rate of 0.05 mm/min was selected as the shear displacement rate in this research.

The calculations of two indispensable parameters, shear resistance τ and average displacement D, are provided in [23] with full descriptions.

3. RESULTS

The residual strength of all the samples was reached thoroughly by the multistage procedure, as shown in Figs. 2–9. It is evident that it took a great deal of time to reach the residual strength, whereas the time it took to reach the peak strength was obviously short. The shear strength criteria are shown on the right side of every figure; they were obtained from the data, which were acquired in one day, shown on the left side of the Bromhead ring shear apparatus.

The residual frictional angles (φ_γ) are summarized in Table 3, along with the corresponding soil properties. The residual frictional angle of the soil samples varied considerably, from 18° to 29°. Notably, the liquid limit, plastic limit and plasticity index increased with the increasing FGP. It is also evident that the residual frictional angle was inversely related to the liquid limit, plastic limit and plasticity index.

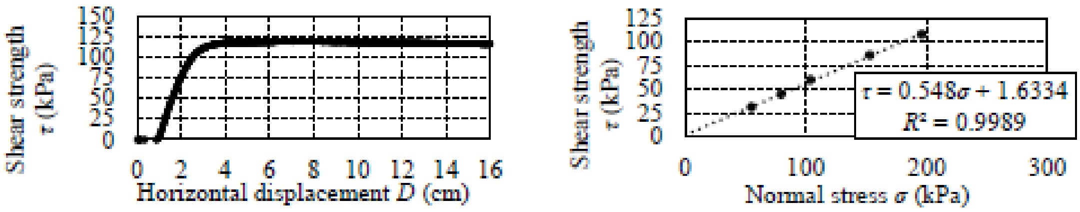

Fig. 2 Shear strength vs. horizontal displacement and shear strength criteria in Sample 1-1

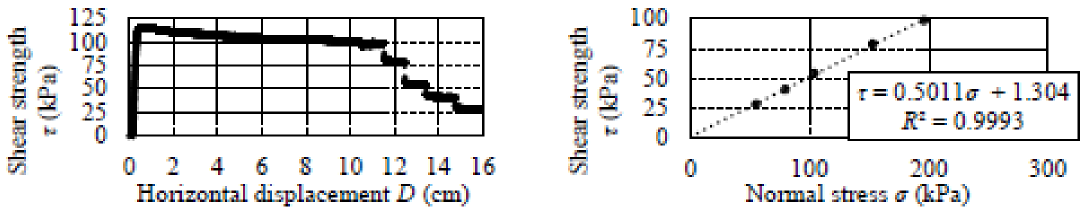

Fig. 3 Shear strength vs. horizontal displacement and shear strength criteria in Sample 2-1

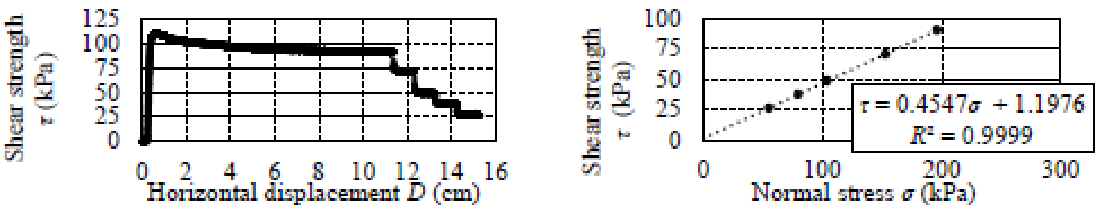

Fig. 4 Shear strength vs. horizontal displacement and shear strength criteria in Sample 3-1

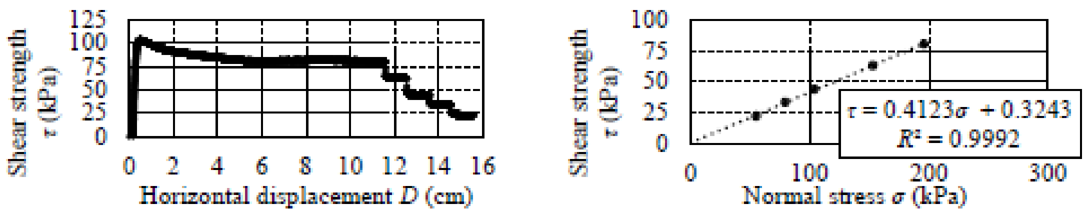

Fig. 5 Shear strength vs. horizontal displacement and shear strength criteria in Sample 4-1

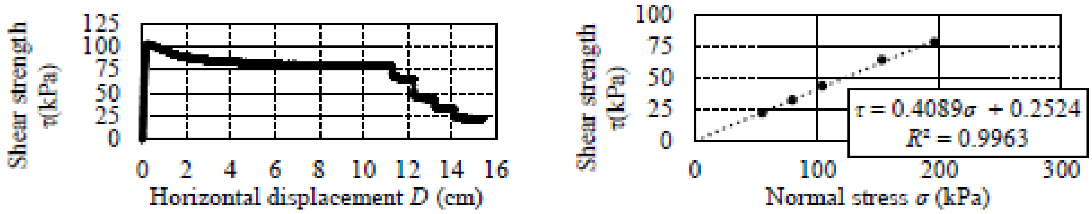

Fig. 6 Shear strength vs. horizontal displacement and shear strength criteria in Sample 5-1

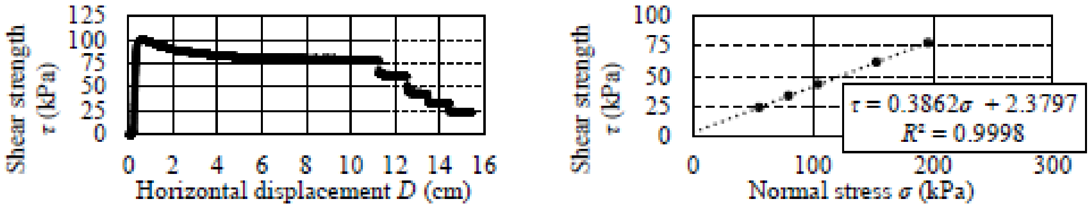

Fig. 7 Shear strength vs. horizontal displacement and shear strength criteria in Sample 6-1

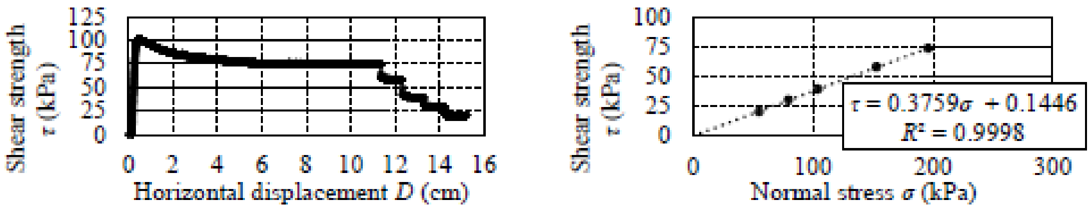

Fig. 8 Shear strength vs. horizontal displacement and shear strength criteria in Sample 7-1

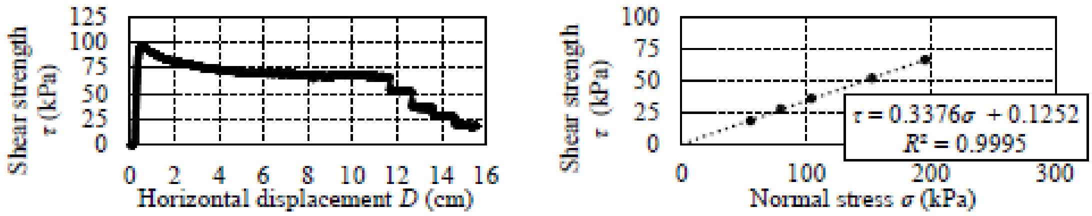

Fig. 9 Shear strength vs. horizontal displacement and shear strength criteria in Sample 8-1

Table 3 Soil properties and residual frictional angle of each sample

Samples	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	φ_γ (°)
1-1	25.10	14.68	10.42	28.72
2-1	28.43	15.08	13.35	26.62
3-1	30.87	15.58	15.29	24.45
4-1	31.50	16.00	15.50	22.41
5-1	32.74	16.96	15.78	22.24
6-1	33.82	18.36	15.46	21.12
7-1	34.45	18.97	15.48	20.60
8-1	36.64	19.49	17.15	18.65

The correlations between the residual frictional angles and the Atterberg limits are given in Figs. 10-12. The data show that the residual frictional angles have a good relationship with the liquid limit, plastic limit and plasticity index. A strong correlation is found between the residual frictional angle data and the liquid limit (ω_L), which can be expressed by the linear relationship, $\varphi_\gamma = -0.9031\ \omega_L + 51.726$, with $R^2 = 0.9796$; a correlation is also found between the residual frictional angle data and the plastic limit (ω_P), which can be expressed by the linear relationship, $\varphi_\gamma = -1.66\ \omega_P + 51.139$, with $R^2 = 0.8557$; similarly, a correlation is found between the residual frictional angle data and the plasticity index (I_P), which can be expressed by the linear relationship, $\varphi_\gamma = -1.4925\ I_P + 45.197$, with $R^2 = 0.8496$.

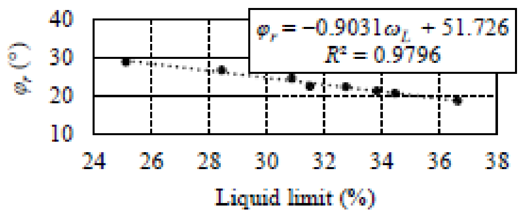

Fig. 10 Residual frictional angle vs. liquid limit

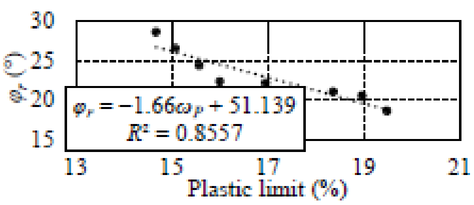

Fig. 11 Residual frictional angle vs. plastic limit

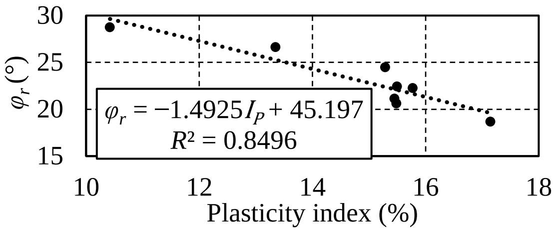

Fig. 12 Residual frictional angle vs. plasticity index

4. DISCUSSIONS

4.1 Compaction tests on all samples

The compaction tests on all the samples, including the original soils (from 1 to 8) created for the reservoir embankment soil (15.1% < the ratio of fine grains < 50%) and the eight samples (from 1-1 to 8-1) used in the Bromhead ring shear apparatus, are shown in Fig. 13. The conditions of the samples (moisture content and dry density) were also determined during shearing in the Bromhead ring shear test, and are shown in the figure by the red points. All the values (red points) for the samples during shearing are given on the right side of the compaction curves. The results of the compaction tests are summarized in Table 4. From this table, the evidence points to the probability that the maximum dry density decreased with the increasing FGP. Similarly, the optimum moisture content increased with the increasing FGP. It seems likely that the surface of the soil for adsorbing water increased with the increasing FGP, resulting in the increase in the optimum moisture content.

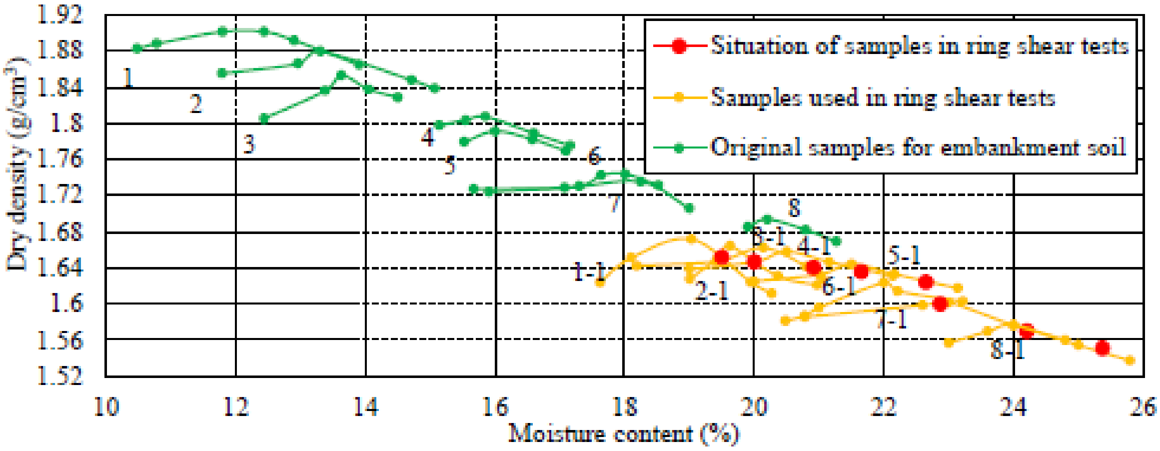

Fig. 13 Compaction curves and conditions of samples in Bromhead ring shear test

Table 4 Summary of compaction tests

Samples	ω_{opt} (%)	ρ_d (g/cm^3)	D_c %
1	12.15	1.90	–
2	13.30	1.88	–
3	13.50	1.85	–
4	15.80	1.81	–
5	17.60	1.76	–
6	18.00	1.74	–
7	18.80	1.73	–
8	20.20	1.69	–
1-1	19.5	1.67	98.79
2-1	19.63	1.66	98.94
3-1	20.14	1.66	98.69
4-1	20.50	1.65	98.65
5-1	21.50	1.64	98.77
6-1	22.05	1.62	98.53
7-1	23.00	1.60	98.02
8-1	24.00	1.58	98.36

ω_{opt}: Optimum moisture content; ρ_d: Maximum dry density; D_c: Degree of compaction

4.2 Use of Atterberg limits to estimate residual frictional angle

Many researches [5–11] have shown the correlation between the residual frictional angle and the Atterberg limits; however, they only focused on fine-grained soils. And, as shown previously, in order to analyze the slope stability of a reservoir embankment, it is necessary to consider the CGP. The current findings expand upon our prior work.

In this research, the samples, whose size was less than 0.425 mm, were used to obtain the residual strength parameter by the Bromhead ring shear test and to acquire the values of the different indexes through physical property tests. The reasons why this size of samples was chosen for this study are as follows: firstly, the size of the samples used for the liquid limit and the plastic limit should be less than 0. 425 mm, based on JIS A 1205; secondly, the initial thickness of the samples used in the Bromhead ring shear apparatus was 0.5 cm. However, Wen [7] pointed out that the residual strength is largely dependent on the clay content, and that the sand fraction has little influence on the residual strength of remolded soil. Li [14] also showed that the correlation between the residual strength and gravel is very weak. Therefore, there is very little difference between the values of the residual frictional angle of the samples used in the Bromhead ring shear apparatus and the residual frictional angles of the practical samples from the reservoir embankment soil. In other words, the formulas for predicting the residual frictional angle by the Atterberg limits in this research can be applied to practical reservoir embankment soil, especially when the time for taking the measurements or the condition of the tests is limited, which would very beneficial to researchers worldwide.

From the left side of Figs. 2–9, the horizontal displacement to the peak strength is very small, less than 0.5 cm. Based on different researches [2, 13, 15], as well as this study, it is difficult to say exactly when the residual strength could be reached in different types of soil.

From Figs. 10–12, the residual frictional angle is seen to decrease with the increase in the liquid limit and the plastic limit, respectively. Similarly, the residual frictional angle shows a decreasing trend with the increase in the plasticity index. Compared with the other indexes in this research, the liquid limit is seen to be better correlated with the residual frictional angle, with $R^2 = 0.9796$.

In this research, the correlations between the residual frictional angle and the Atterberg limits were shown for just one type of soil. Future work, focusing on different types of soil and pointing out a more precise formula for predicting the residual shear strength, should be done.

5. CONCLUSIONS

The aim of this research was to find the correlations for predicting the residual frictional angle for reservoir embankment soil by the Atterberg limits which could be obtained in a short time. This paper described a series of drained ring shear tests, on eight kinds of reservoir embankment soil samples under normal stress levels ranging from 50 to 200 kPa, by the multistage procedure with the Bromhead ring shear apparatus and samples that were less than 0.425 mm in size. The results presented in this paper have led to the following general conclusions:

A long horizontal displacement was needed to reach the residual strength state. Compared with the soil in other research, it was difficult to say exactly when the constant value could be reached with the different soil samples in this research; however, the peak strength state could be obtained in a short horizontal displacement, namely, less than 0.5 cm.

The residual frictional angle was in inverse correlation to the liquid limit, plastic limit and plasticity index. With the increasing ratio of FGP, the liquid limit, plastic limit and plasticity index increased, whereas the residual frictional angle decreased. These results follow the basic theory of geotechnical engineering. Compared with the other indexes, the liquid limit had a better correlation for predicting the residual frictional angle by the linear relationship in such a soil, which provided a convenient perspective with high accuracy for application in geotechnical engineering.

From a research viewpoint, the correlations demonstrated in this study appear feasible, although the results were obtained with a limited number of samples. The predicted formulas can be applied by practicing geotechnical engineers to calculate the residual friction angle value if the index properties of the soil are available.

6. ACKNOWLEDGEMENTS

The authors would like to gratefully acknowledge Mr. Akira Kawahara, Chugoku-Shikoku Regional Agricultural Administration Office, and Mr. Yoshifumi Watanabe, Ehime Prefectural Government Office, for providing the soil materials which were suitable for the investigations in this paper.

7. REFERENCES

[1] Marcuson, W.F., Hynes, M.E., and Franklin, A.G., Evaluation and Use of Residual Strength in Seismic Safety Analysis of Embankments, Earthquake Spectra, Vol. 6, Issue 3, 1990, pp. 529–572.

[2] Fang, C., Shimizu, H., Nishimura, S., Hiramatsu, K., Onishi, T., and Nishiyama, T., Seismic risk evaluation of irrigation tanks: A case study in Ibigawa-Cyo, Gifu Prefecture, Japan, International Journal of GEOMATE, 2018, Vol. 14, Issue 41, pp. 1–6.

[3] Insley, A. E., Chatterji, P.K., and Smith, L.B., Use of residual strength for stability analyses of embankment foundations containing preexisting failure surfaces, Canadian Geotechnical Journal, Vol. 14, Issue 3, 1977, pp. 408–428.

[4] Lupini, J. F., Skinner, A. E. and Vaughan P. R., Drained residual strength of cohesive soils, Géotechnique, Vol. 31, Issue 2, 1981, pp. 181–213.

[5] Bishop, A. W., Green, G. E., Garga, V. K., Andresen, A. and Brown, J. D., A new ring shear apparatus and its application to

measurement of residual strength, Géotechnique, Vol. 21, Issue 4, 1971, pp. 273–328.
[6] Stark, T. D., Choi, H., and McCone, S., Drained shear strength parameters for analysis of landslides, Journal of Geotechnical and Geo Environmental Engineering, ASCE, Vol. 131, Issue 5, 2005, pp. 575–588.
[7] Wen, B. P., Aydin, A., Duzgoren-Aydin, N. S., Li, Y. R., Chen, Y.R. and Xiao, S. D., Residual strength of slip zones of large landslides in the Three Gorges area, China. Engineering Geology, Vol. 93, Issues 3–4, 2007, pp. 82–98.
[8] Hayden, C. P., Purchase-Sanborn, K. and Dewoolkar, M., Comparison of site-specific and empirical correlations for drained residual shear strength, Géotechnique, Vol. 68, Issue 12, 2018, pp. 1099–1108.
[9] Voight, B., Correlation between Atterberg plasticity limits and residual shear strength of natural soil, Géotechnique, Vol. 23, Issue 2, 1973, pp. 265–267.
[10] Seyeek, J., Residual shear strength of soils, Bulletin of Engineering Geology and the Environment, Vol. 17, Issue 1, 1978, pp. 73–75.
[11] De, P. K. and Furdas, B., Discussion – Correlation between Atterberg plasticity limits and residual shear strength of natural soils, Géotechnique, Vol. 23, Issue 4, 1973, pp. 600–601.
[12] WESLEY, L. D., Residual strength of clay and correlations using Atterberg limits, Géotechnique, Vol. 53, Issue 7, 2003, pp. 669–672.
[13] Chen, X. P., Liu, D., Residual strength of slip zone soils, Landslides, Vol. 11, Issue 2, 2014, pp. 305–314.
[14] Li, Y. R., Wen, B. P., Aydind, A. and Ju, N. P., Ring shear tests on slip zone soils of three giant landslides in the Three Gorges Project area, Engineering Geology, Vol. 154, 2013, pp. 106–115.
[15] Skempton, A. W., Residual strength of clays in landslides, folded strata and the laboratory, Géotechnique, Vol. 35, Issue 1, 1985, pp. 3–18.
[16] Townsend, F. C., Gilbert, P. A., Tests to measure residual strength of some clay shales, Géotechnique, Vol. 23, Issue 2, 1973, pp. 267–271.
[17] Hvorslev, M. J., Torsion shear tests and their place in the determination of the shearing resistance of soils, Proceedings of American Society Material 39, 1939, pp. 999–1022.
[18] Stark, T. D. and Eid, H. T., Comparison of field and laboratory residual strengths, Proceedings, ASCE specialty conference stability and performance of slopes and embankments-ll. University of California, Berkeley, CA, ASCE, New York, 1992.
[19] Stark, T. D. and Vettel, J. J., Bromhead ring shear test procedure, Geotechnical Testing Journal, Vol. 15, Issue 1, 1992, pp. 24–32.
[20] Skempton, A. W., Long-term stability of clay slopes, Géotechnique, Vol. 14, Issue 2, 1964, pp. 77–102.
[21] So, E. K. and Okada, F., Some factors influencing the residual strength of remoulded clays, Soils and Foundations, Vol. 18, Issue 4, 1978, pp. 107–118.
[22] Scaringi, G., and Di Maio, C., Influence of displacement rate on residual shear strength of clays. Procedia Earth and Planetary Science, 2016, Vol. 16, pp. 137–145.
[23] Bromhead, E.N., A simple ring shear apparatus, Ground engineering, Vol. 12, Issue 5, 1979, pp. 40–44**.**