貯水池盛土材料の諸指数と残留摩擦角の対応に関する実験的検討
Experimental study on estimating the residual frictional angle of soils by available indexes for agricultural reservoir embankments

○房 晨* 清水英良** 西山竜朗* 西村眞一* 今泉文寿***
(Chen Fang) (Hideyoshi Shimizu) (Tatsuro Nishiyama) (Shin-Ichi Nishimura) (Fumitoshi Imaizumi)

1. Introduction

Residual strength parameters have received much attention in recent years due to their importance in stability analyses when considering the effect of large earthquakes on the settlement of foundations and evaluating the stability of a slope which has experienced a landslide. Residual strength parameters, including residual frictional angle ϕ_r and cohesion, can be determined by laboratory tests. It should be noted, however, that the procedure for obtaining the residual strength parameters through laboratory shear tests is complex and costly. Lupini et al. (1981) showed that the non-zero cohesion component in cohesive soil comes from low normal stress rather than from the nature of the soil. Therefore, in this study, the residual strength of slip zones was examined in terms of the residual frictional angle. Fang et al. (2019) estimated the residual frictional angle by the Atterberg limits for reservoir embankment soils by only considering the limited ratio of the fine-grained particles (FGPs) which is between 15% and 50%. The aim of this study is to find an effective way to estimate the residual frictional angle of soils by the available indexes considering a wider scope of FGPs.

2. Materials and methodology

Remolded soil samples were used in this study as it was demonstrated by Bishop et al. (1971) that the residual stress is unaffected by the initial structure of the soil. The samples, belonging to decomposed granite soil, were taken from Hojo, Matsuyama, Japan, as suitable material for reservoir embankments. The standard for reservoir embankment soils, based on the ratio of FGPs, is proposed according to the Japanese Institute of Country-ology and Engineering. For this purpose, fifteen different soil samples were artificially prepared by varying the FGPs using a 0.075-mm sieve. The ratios of FGPs (γ_{FGP}) were from 0% to 100%, as shown in Table 1.

Table 1 Details on soil properties and residual frictional angle of each sample, γ_{FGP} of original sample from Matsuyama city is 35.7%.

γ_{FGP} (%)	ω_L (%)	ω_P (%)	I_L (%)	ϕ_r (°)
0	×	×	×	32.9
10.0	24.6	×	×	30.9
15.1	25.1	14.7	10.4	27.8
20.0	28.4	15.1	13.3	25.8
25.0	30.9	15.6	15.3	23.7
30.0	31.5	16.0	15.5	21.7
35.7	32.7	17.0	15.8	21.5
40.0	33.8	18.4	15.5	20.4
45.0	34.5	19.0	15.5	19.9
49.5	36.6	19.5	17.1	18.0
60.0	40.2	20.0	20.2	16.0
70.0	42.0	20.4	21.6	14.2
80.0	45.2	20.8	24.4	13.9
90.0	46.3	21.2	25.1	13.9
100	47.0	21.7	25.3	14.0

* × means the value could not be obtained.

In this research, a grain size analysis, liquid limit test, plastic limit test and ring shear test were conducted for all samples based on the standards of the Japanese Geotechnical Society. According to the JIS A 1205 test guide, the size of each sample should be less than 0.425 mm in both liquid limit and plastic limit tests. Therefore, soil samples that passed through a 0.425-mm sieve were used in this study.

3. Experimental results and discussion

Figure 1 shows shear stress versus horizontal displacement in different samples. The shear stresses at the peak and residual states were named the peak strength and the residual strength, respectively. Firstly, it is clearly seen that the residual state was almost obtained for all samples. With an increase in the FGP fraction, the peak strength and residual strength, respectively, decreased. It is found that the difference between the peak strength and the residual strength increases with an increase in the ratio of FGPs through

* 岐阜大学 応用生物科学部 (Faculty of Applied Biological Sciences, Gifu University)
** 岐阜大学 名誉教授 (Emeritus Professor, Gifu University, Japan)
***静岡大学 農学部 (Faculty of Agriculture, Shizuoka University)
キーワード:斜面安定,残留摩擦角,細粒分,予測式,リングせん断試験 (Slope stability, residual frictional angle, fine-grained particle, estimation formula, ring shear test)

the calculation, which implies that the greater the FGP fraction is, the stronger the post-peak intensity attenuation is.

At the same time, when the residual state is obtained, another phenomenon that has to be noted in the shear tests is fluctuations in shear stress. Some representative examples under normal stress of 201 kPa were selected, as shown in Figure 2. A consistent theory that has been reported in a lot of literature is that the residual state is obtained when the phenomenon of particle orientation occurs. From Figure 2, even after a long horizontal displacement in the shearing process, a small amplitude of fluctuation still exists. Thus, it is evident that as the FGP fraction increases, the amplitude of such fluctuations under the same normal stress decreases. Therefore, the reason for the fluctuation in shear stress under the residual state is attributed to the coarse-grained particles in the soil samples.

The residual frictional angle can be calculated based on the data in Figure 1. The residual frictional angles of all the soil samples are summarized in Table 1, along with the soil properties. Notably, it is seen that the residual frictional angle of the soil samples varies considerably, from 14° to 33°. It is also evident that the liquid limit, plastic limit and plasticity index increase with the increasing FGPs, whereas the residual frictional angle is inversely related to the liquid limit, plastic limit, plasticity index and ratio of FGPs.

The available indexes were selected here, including the liquid limit, plastic limit, plasticity index and the ratio of FGPs. The correlation between the residual frictional angle and all the available indexes was determined. After a comparison, it was found that the ratio of FGPs and the liquid limit are better indexes for estimating the residual frictional angle due to the high value of the determination coefficient, R^2, as shown in Figure 3. Besides that, it is clearly seen that the residual frictional angle keeps almost same when the ratio of FGP is more than 90%, which is possible due to the contact of coarse-grained particles hardly occurring.

From a research viewpoint, this study has proposed formulas for reservoir embankments considering a wider scope of FGPs in one type of soil. In the next research, focus should be placed on other types of soil.

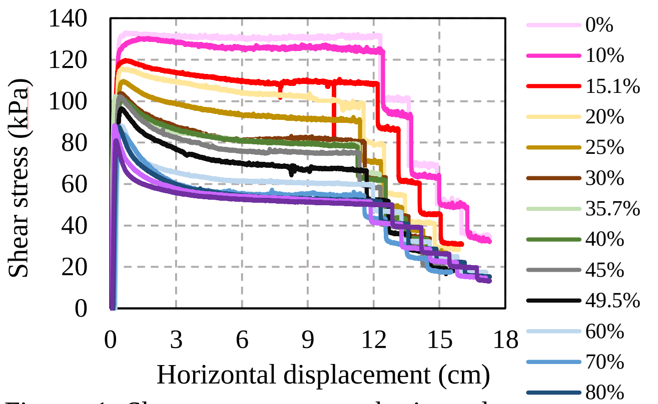

Figure 1 Shear stress versus horizontal displacement in different soil samples

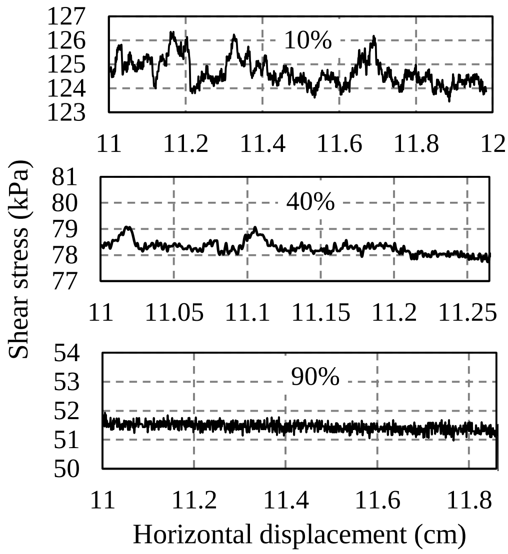

Figure 2 Fluctuations in shear stress under normal stress of 201 kPa at different ratios of FGPs

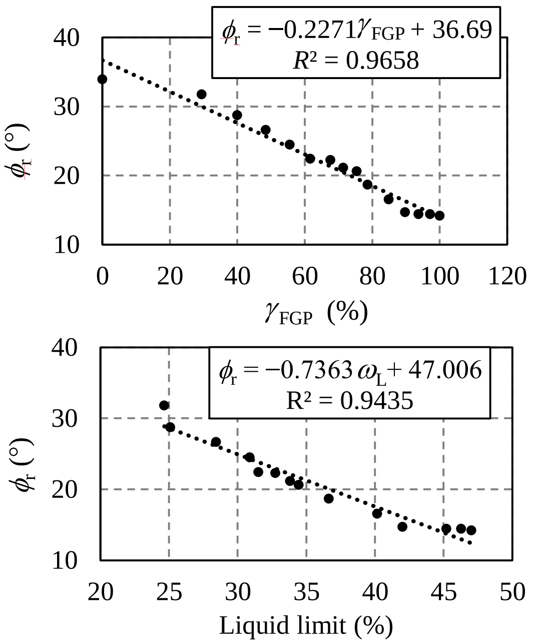

Figure 3 Residual frictional angle versus ratio of FGPs and liquid limit

References

Bishop et al. (1971) A new ring shear apparatus and its application to measurement of residual stress, *Géotechnique*, 21 (4): 273–328.

Fang et al. (2019) Predicting residual fictional angle by Atterberg limits for reservoir embankment soils, *Int. J. GEOMATE*, 17(63): 111–118.

Li et al. (2017) Effect of over-consolidation and shear rate on the residual stress of soils of silty sand in the Three Gorges Reservoir, *Sci. Rep.*, 7: 5503.

Lupini et al. (1981) Drained residual stress of cohesive soils, *Géotechnique*, 31(2): 181–213.