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Comparison of shear characteristics of undisturbed and remoulded Bangkok clay

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Abstract

Residual effective stress measurement tests, unconfined compressions tests and triaxial compression tests were performed on undisturbed and remoulded clay from Bangkok, Thailand, to investigate the aging effects on shear characteristics of clay. The undisturbed samples were carefully trimmed soil sample from sampling tube. The remoulded samples were reconstituted from a slurry and consolidated at the same effective overburden pressure. The main purpose of the present study is to compare the stress-strain-strength behavior of the undisturbed and the remoulded specimens of Bangkok clay.

Quantitative test results show that the shear strength of the undisturbed samples are greater than those of the remolded samples. This difference is attributed to the fact that the soil structure of the undisturbed samples offers greater resistance to external loading compared to the remoulded samples in which the soil structure has been destroyed. The similar tendency was also obtained from triaxial test results. In addition, the quantitative relationships between strength and residual effective stress for the undisturbed and the remoulded samples were investigated. The residual effective stress of undisturbed samples is greater than those of remolded samples at the same consolidation pressure. Reasonable correspondence between the residual effective stress and unconfined compressive strength was obtained. As a result, when the quality of the unconfined compressive strength is evaluated during ground stability analysis, it is effective to measure the residual effective stress which remains before unconfined compression tests are carried out.

1. Introduction

The mechanical behavior of clay is typically investigated in the laboratory by tests on either natural samples or remoulded samples. At this stage, the remoulded and reconsolidated clays are frequently used to avoid the scatter of experimental results obtained from natural clays, and to surmount the difficulty of obtaining natural clays to investigate their mechanical properties. The remoulded clays are also used in model tests. However, strength-deformation characteristics and failure mode in laboratory tests may differ from those in the field. The difference between the undisturbed and the remoulded specimens is the existence of soil structure in the former due to the method of deposition in the field. The remoulded specimens have no similar soil structure. Therefore, it is necessary to consider differences in soil structure in stability evaluation. The questions are whether these laboratory results really reflect in-situ behavior, and do they gave proper answers the design analyses and safety evaluation?

The importance of aging effects on the mechanical behavior of clay was first reported by BJERRUM[1]. He pointed out that the difference between young and aged clay is explained by secondary compression or delayed compression, i.e. aged clay is characterized by an increase in consolidation yield stress p_c and decrease in the void ratio due to secondary consolidation. MESRI and GODLEWSKI[2] investigated one dimensional compressibility of Leda clay, which is well known as a cemented clay. In their figure, the compression index C_c (defined as de/d(log p)) and coefficient of secondary compression C_α (defined as de/d(log t)) of both undisturbed and remoulded samples were plotted versus consolidation pressure p respectively. They found that both C_c and C_α of undisturbed samples have clear peaks whereas they remain constant with p for remoulded samples. According to JAMIOLKOWSKI et al.[3] the stress-strain relation of a highly structured Canadian clay was extremely brittle when the consolidation pressure was smaller than the consolidation yield pressure p_c. On the other hand, when the consolidation pressure exceeded the p_c, the clay became ductile, because the clay structure formed by the aging effect was destroyed by consolidation under pressure far exceeding the p_c. KAMON and NAGAO[4] investigated the mechanical properties of artificially cemented clays which were made by mixing 5% cement by weight. These artificially cemented clays showed larger p_c, larger compressibility at the consolidation pressure over p_c and larger undrained shear strength in the over-consolidation region than did non-cemented clay.

Effects of consolidation time on the undrained shear strength have been studied by many researchers[5)-12)]. Such studies found that the undrained shear strength increased with the length of consolidation. TSUCHIDA et al.[13)] reported that remoulded clay samples whose mechanical properties were similar to those of lightly aged clay could be produced in the laboratory by consolidation of clay slurry at a high temperature, followed by cooling after completion of consolidation. This resulted from the fact that high temperatures accelerate chemical reactions in clay particles.

Unconfined compression tests have been widely used in Japan for evaluating undrained shear strengths of clay samples, but, the unconfined compressive strengths are usually scattered, because the derived unconfined compression test itself is performed under unstable confining pressure originating from the residual effective stress of the individual specimen. In view of these circumstances, the effects of stress release and mechanical disturbance on the undrained shear strength characteristics of cohesive soils have been investigated. This work shows unconfined compressive strength depends strongly on the residual effective stress before undrained shear[14)-17)]. By measuring the suction value when performing unconfined compression test, the degree of sample disturbance can be evaluated from the magnitude of residual effective stress, and in-situ undrained shear strength can be evaluated[14)-17)]. Therefore, when the quality of the unconfined compressive strength is evaluated during stability analysis of ground, it is effective to measure the residual effective stress which remains before unconfined compression tests are carried out.

Quantitative comparisons of undrained shear strength for undisturbed and remoulded samples have been investigated [18)-21)] and the differences are gradually being understood. The applicability of the results are not, as yet, entirely clear. Much additional research in this area is thus required to provide further comparative data. In addition, the influence of variation in calcite ($CaCO_3$) content on strength-deformation characteristics have been investigated and quantitative relationships between $CaCO_3$ content and strength- deformation characteristics for cohesive soils have been developed[22-25)].

The main purpose of our present study is to compare the stress-strain-strength behavior of undisturbed and remoulded specimens of Bangkok clay. A larger data base may then enable a more definitive assessment of the difference in undrained shear

Figure 1 Map of lower central plain in the Kingdom of Thailand

strength between undisturbed and remoulded clay to be made.

2. Soil samples and testing program

The Chao Phraya Plain in Bangkok consists of a broad, deep basin filled with sedimentary soil deposits comprising alternating layers of sand, gravel and clay. The depth to bedrock varies between approximately 550 and 2000 m. The term Bangkok clay refers to the uppermost marine clay which is found in the lower deltaic area of the Bangkok Plain. This extends 200 to 250 km East-West and 250 to 300 km North-South (Figure 1). The thickness of soft Bangkok clay in the upper layer varies from 12 to 20 m towards the Gulf, whereas the total clay layer (including the lower stiff Bangkok clay) is about 15 to 30m. According to ESCAP[26)], deposition of soft Bangkok clay occurred over a short period approximately 4000 years B.P., and it was exposed above the sea about 2700 years B.P.. This clay has not been subjected to geological over-consolidation by over-stressing after deposition[27)].

Site investigations were carried out at the Nong Ngu Hao (NNH) site (Figure 2). NNH is located in the suburbs of Bangkok, 15 km west of the city center. The stratigraphy and basic soil properties at the NNH site are summarized in Figure 3. Weathered clay forms a superficial crust down to about 2 m depth. Soft Bangkok clay extends from 2 m to 15.5 m depth. The density profile of soil particles (ρ_s) is given in Figure 3(a). The range of (ρ_s) varies between 2.75 and 2.78g/cm^3, indicating

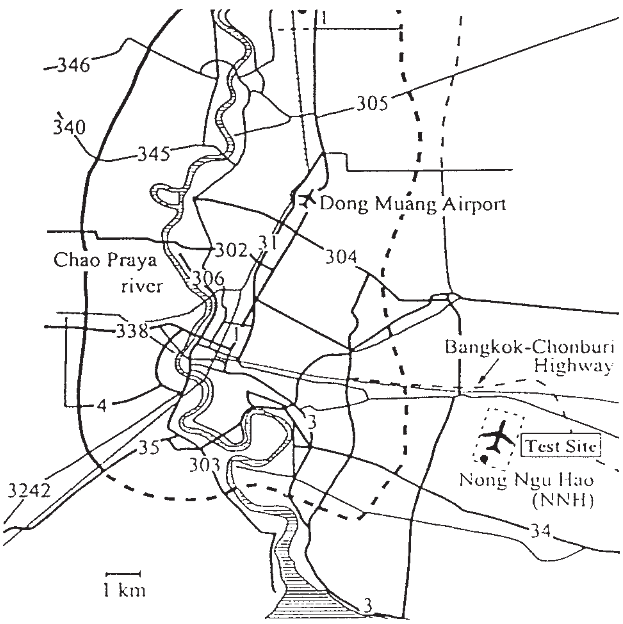

Figure 2 Test site in Bangkok area (Nong Ngoo Hao site)

rather large and uniform density compared to a typical Japanese marine clays. The grain-size composition of the samples from this site consist of very fine particles: the portion of clay particles exceeds 60% at all most depths, and the content of sand is very small. A stiff clay layer below extends from 15.5m to 21m depth. This in turn overlies a dense sand layer.

In this soft marine clay layer, natural water content (w_n) is almost equal to liquid limit (w_L) about 3 to 7m depth, but it w_n becomes slightly smaller the w_L (Figure 3(c)), below this depth thereby decreasing the liquidity index (I_L) of 1.0. Plasticity index (I_p) increases with depth from 70 to 90 to about 9m of the depth, below which it becomes constant about 70 (Figure 3(d)). The order of liquidity index (I_L) changes at 10m depth. For the upper parts of this depth, I_L is near unity, and below this depth I_L reduces to values as small as 0.5(Figure 3(e)). Unconfined compressive strength q_u value is nearly constant between 4 and 9m of the depth and is around 45kPa. At the depths lower than 11m, however, q_u increases about 11.5 to 15m depth and is around 90 to 120kPa(Figure 3(f)). The I_p, I_L and q_u are apparently different between the upper and lower layers, the boundary being at a depth of 10m.

Table 1 Index properties of samples

Depth(m)	ρ_s(g/cm³)	w_n(%)	w_L(%)	w_p(%)	I_p	Sand(%)	Silt(%)	Clay(%)
2.85～2.95	2.769	103.6	99.8	29.3	70.5	0.9	33.9	65.2
4.85～4.95	2.763	101.1	102.9	29.3	73.6	0.7	26.5	72.8
6.15～6.25	2.776	108.3	110.6	30.4	80.2	0.8	26.1	73.1
6.85～6.95	2.754	108.5	113.4	32.4	81.0	0.3	20.2	79.5
8.85～8.95	2.761	107.9	122.3	32.8	89.5	1.9	13.6	84.5
11.65～11.75	2.755	81.0	97.5	29.8	67.7	9.6	27.3	63.1
13.75～13.91	2.726	63.1	95.9	28.7	67.2	1.8	20.4	77.8

Residual effective stress measurement tests, unconfined compressions tests and triaxial compression tests were performed on the undisturbed and the remoulded clays from Bangkok to investigate the aging effects on the shear characteristics of the clay. The undisturbed specimens were carefully trimmed from soil samples taken from the sampling tube. The undisturbed samples used in the present study were sampled from thin wall using the Japanese standard fixed piston sampler. Remoulded samples were reconstituted from a slurry and consolidated at the same effective overburden pressure. Index properties of these samples are summarized in Table 1, grading curves of the samples are given in Figure 4.

Unconfined compression tests were carried out following the testing standard of the Japan Geotechnical Society. The diameters and the heights of the specimens were 35mm and 80mm, respectively. Shearing was carried out at an axial strain rate of 1%/min. Measurement of residual effective stress was made before the unconfined compression test was conducted. For this purpose, the soil specimens trimmed for the unconfined

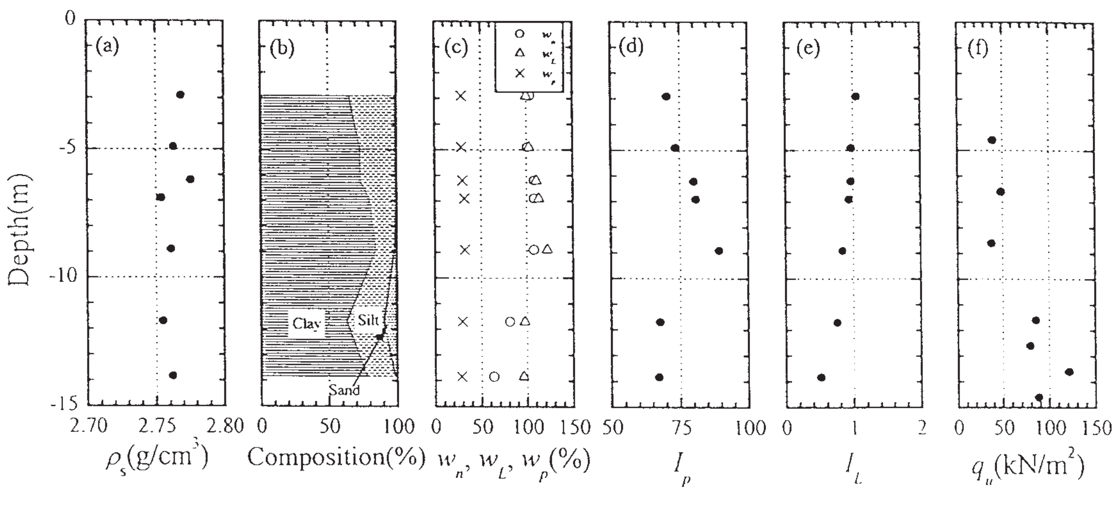

Figure 3 The stratigraphy, with together basic soil properties at Nong Ngoo Hao site

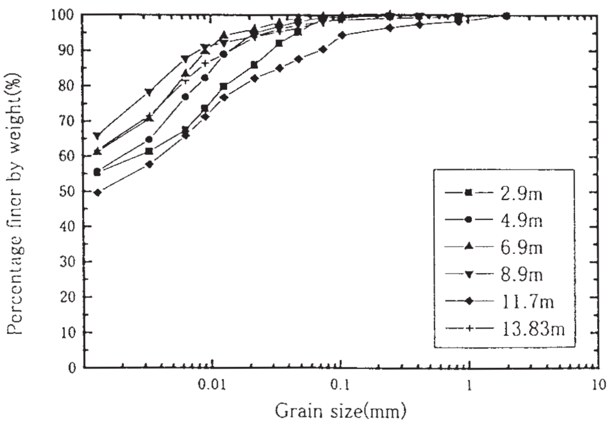

Figure 4 Grading curves of the samples

compression tests were placed on ceramic discs saturated with air-free water, and having an air entry value of 200 kPa. The residual effective stress tests were carried out until a constant value was obtained. The sizes of the specimens used in the triaxial test were the same as those of the unconfined compression tests. The specimens were consolidated along the K_o–consolidation path to the in-situ effective stress, while allowing lateral drainage. The coefficient of earth pressure at rest (K_o) was assumed to be 0.5, and back pressure of 200 kPa was applied during consolidation. After consolidation was completed, the specimen was sheared under undrained condition at an axial strain rate of 0.1%/min[28]. The test procedures for the undisturbed and remoulded samples were identical.

3. Test results and discussions

The variation of residual effective stress (σ_r') with elapsed time in undisturbed and remoulded samples of Bangkok clay at 6.4m(σ_{vc}'=40.8kPa) and 12.4m(σ_{vc}'=106.7kPa) are given in Figure 5, where the effective vertical consolidation pressure is denoted as σ_{vc}' and the absolute value of negative pore pressure equals residual effective stress. The residual effective stress of undisturbed and remoulded samples of σ_{vc}'=40.8kPa rapidly decreases with elapsed time, and reaches constant values of 18kPa and 13.5 kPa at about 200 seconds, respectively. The residual effective stress of undisturbed sample with σ_{vc}'=106.7kPa rapidly decreased with elapsed time, and reached constant value of 34kPa at about 400 seconds. In contrast, the remoulded sample decreased gradually with elapsed time, only reaching constant value of 31.4kPa after 800 seconds or more. The σ_r' of undisturbed samples were 33% (σ_{vc}'=40.8kPa) and 8% (σ_{vc}'=106.7kPa) larger than that of remouded sample, irrespective of the same consolidation pressure. Therefore, it can be seen that the soil structure of undisturbed samples easily maintains the residual effective stress due to aging effect. No significance difference in pore pressure was observed in the sample tested at σ_{vc}'=40.8kPa. If the quality of sampling is poor, the value of residual effective stress becomes smaller, resulting in a decreased value for the unconfined compressive strength q_u owing to swelling.

Figure 6 shows the stress-strain behavior of undisturbed and remoulded samples obtained from unconfined compression tests. It is evident that the stress-strain curves of the undisturbed samples have a pronounced peak, whereas no such peak appears in remouded samples irrespective of effective overburden pressure. The peak stress is observed in all samples at axial strain of about 2%. In addition, when the stress increases rapidly and strain reaches about 2%, stress subsequently decreases. The unconfined compressive strength (q_u) of undisturbed sample is about 100% (σ_{vc}'=40.8kPa) and

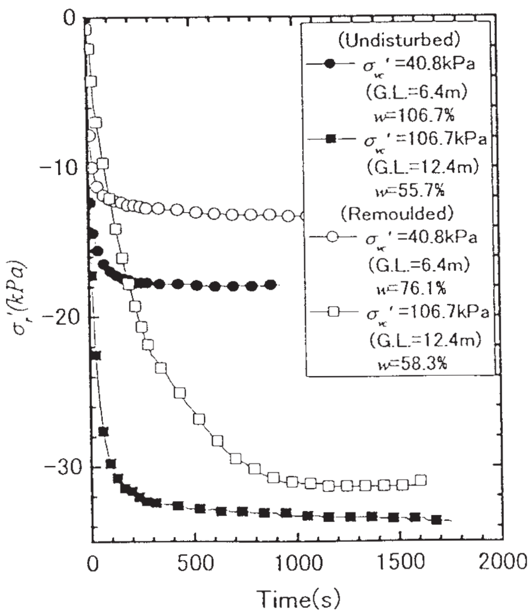

Figure 5 Variation of residual effective stress with elapsed time

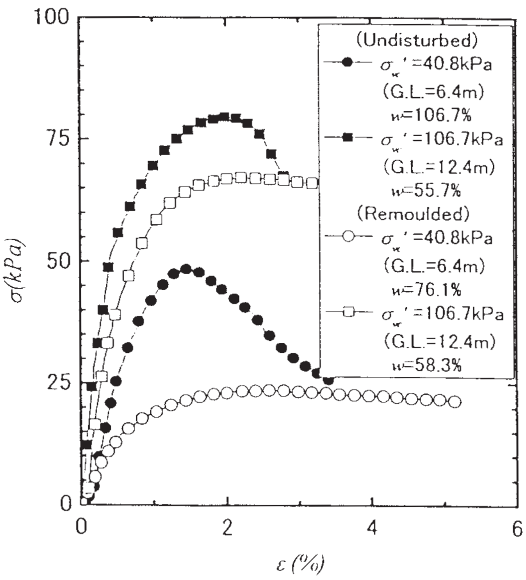

Figure 6 Comparison of stress-strain curves obtain from unconfined compression tests

18%(σ_{vc}'=106.7kPa) greater than that of remouded sample at the same consolidation pressure. This difference in strength increases with the difference in water content in both samples, i.e., the water content of the undisturbed sample is about 30% larger than that of the remoulded sample in the case of σ_{vc}'=40.8kPa. This result confirms that reported by other reports[18)-21)]. The stress-strain behavior of Bangkok clays has similar characteristics to that of Canadian clay, i.e. undisturbed samples show brittle behavior, whereas remoulded samples show ductile behavior[3)].

The primary reason for the differences in stress-strain-strength behavior, as suggested above, is most probably the difference in soil fabric between the undisturbed and the remoulded specimens. Quantitative test results show that the strength characteristics of undisturbed samples are greater than those of remoulded samples. This difference may be attributed to the fact that the soil structure of the undisturbed samples offers greater resistance to external loading than does the remoulded samples, in which the soil structure has been destroyed. This means that reduction of the unconfined compressive strength q_u may be caused by loss of the residual effective stress. This also suggests the existence of a strong correlation between q_u and residual effective stress.

Figure 7 shows typical stress-strain curves of undisturbed and remoulded samples in triaxial compression tests, where q=principal stress difference σ_v-σ_h, σ_v=total vertical stress, σ_h=total horizontal stress. As seen in the figure, the stress-strain curves of undisturbed samples have pronounced peaks, whereas such peaks do not appear in remouded samples irrespective of effective overburden pressure. The peak stress is again observed at axial strain of about 1% in all samples. In addition, when the stress increases rapidly and the strain reaches about 1%, stress decrease follows. The difference between the undisturbed and remoulded specimens is the existence of soil structure in the former, due to method of deposition and in-situ creep effects. There is no similar soil structure in the remoulded specimens. In addition, even when the field sampling was not truly undisturbed and when the in-situ structure was disturbed by reconsolidation to stress much higher than that in-situ, the remaining structure was still much more resistant to imposed shear than were the remoulded specimens.

The principal stress difference is about 50% (σ_{vc}'=40.8kPa) and 7% (σ_{vc}'=106.7kPa) greater than that of remouded samples at the same consolidation pressure. This difference of strength again increases with the difference in the water content of the samples, i.e., the water content of the undisturbed samples are about 27% (σ_{vc}'=40.8kPa) and 3% (σ_{vc}'=106.7kPa) larger than their remoulded equivalents. This result also agrees with that reported by other reports[18)-21)]. Loss of the residual effective stress is not necessarily brought about by the disturbance of soil structures. In case of where the soil structure is undamaged and only the σ_r' is lost, the real stress-strain behavior may be obtained if the in situ effective stress is applied to the specimen, i.e., confining pressure technique using triaxial apparatus is effective[5)].

The effective stress path results of undisturbed and remoulded samples are compared in Figure 8, where p'=mean effective stress $(\sigma_v'+2\sigma_h')/3$, σ_v'=effective vertical stress, and σ_h'= effective horizontal stress. For all samples, the effective stress paths progress almost vertically, i.e. elastically, from the completion point of the consolidation. After the effective stress path reaches the extended yield surface, plastic strain is

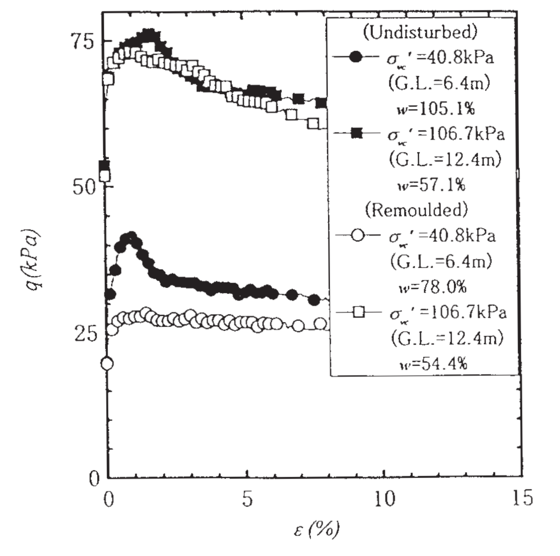

Figure 7 Comparison of stress-strain curves obtained from anisotropically consolidated triaxial compression tests

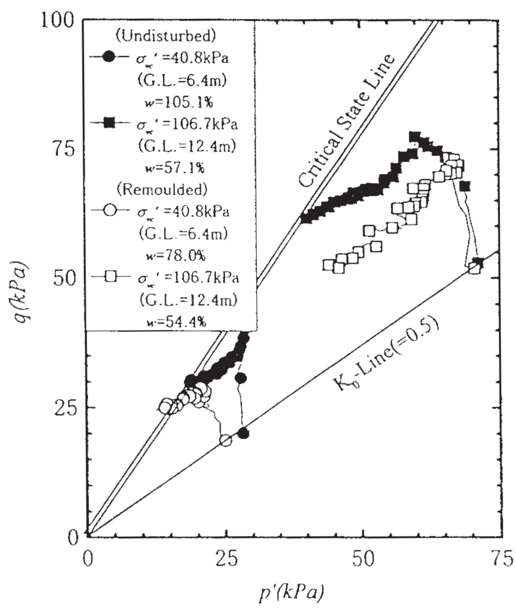

Figure 8 Comparison of effective stress path obtained from anisotropically consolidated triaxial compression tests

pronounced. This progresses with further yielding up to the critical state. The stress paths are characterized by sharp reversal as they approach the critical state line, and thereafter they tend to proceed along that line. The magnitude of this elastic portion can thus be considered to be dependent on the viscoplastic component, which is significantly related to soil structure. This difference, as noted above, may be attributed to the fact that the soil structure of the undisturbed samples offers greater resistance to external loading than does the remoulded samples in which the structure has been destroyed.

4. Conclusions

Unconfined compression tests with measurement of residual effective stress and anisotropically consolidated triaxial compression tests were performed on undisturbed and remoulded clay from Bangkok, Thailand, to investigate the aging effects on the shear characteristics of clay.

Quantitative test results show that strength characteristics of undisturbed samples are greater than those of remoulded samples. This difference is attributed to the fact that the soil structure of the undisturbed samples offers greater resistance to external loading compared to the remoulded samples in which the soil structure has been destroyed. The same results were also obtained from triaxial test results. In addition, the quantitative relationships between strength and residual effective stress for undisturbed and remoulded samples were investigated.

The residual effective stress of undisturbed samples is greater than those of remoulded samples at the same consolidation pressure. Reasonable correspondence between the residual effective stress and unconfined compressive strength was obtained. As a result, when the quality of the unconfined compressive strength is evaluated during ground stability analysis, it is effective to measure residual effective stress which remains before unconfined compression tests are carried out. This study offers the designer a better understanding of the mechanical behavior of clay foundations, leading to refinement of existing construction technology.

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Appendix

*:in Japanese , **: in Japanese with English abstract