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SUCTION AND SHEAR WAVE VELOCITY MEASUREMENTS FOR ASSESSING SAMPLE QUALITY

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Abstract: Sample quality is very important for obtaining reliable geotechnical parameters, especially because the reliability design method has been recently introduced into geotechnical engineering (for example, Eurocode 7). The sample quality is usually assessed by comparing the values of strength, Young's modulus and strain at failure from unconfined compression test as well as the values of preconsolidation pressure, compression index, and volumetric strain at in situ stresses from oedometer test. However, since the assessment criteria are based on past experience, the above conventional methods should be examined carefully in order to explain whether they can or cannot be applied to the layers tested. In addition, it should be noted that they are destructive, i.e., after assessing the specimen quality, it is cannot be used for testing anymore. In this paper, the possibility of assessing a sample quality by suction (p'_r) and shear wave velocity (v_s) is examined.

1. INTRODUCTION

It is well known that sample quality is essential for exact measurements of geotechnical parameters in laboratory testing. In practice, however, sample is taken under various conditions and it is very difficult for designers or persons who conduct laboratory test to confirm under what conditions the sample is collected at the site. Therefore, the methods for assessing the sample quality and reasonable criteria of this assessment ought to be established.

As will be discussed later in more detail, until now many assessment methods and their criteria have been proposed by researchers. For example, typical indices of sample quality are compression strength (q_u), strain at failure (ε_f) and Young's modulus (E) from the unconfined compression test. The sample quality can also be assessed from oedometer test, for example, by the values of the pre-consolidation pressure (p_c), compression index (C_c), volume change under in situ stress conditions (ε_{v0}), including change in void ratio (Δe), and so on. However, the most serious drawback of these methods is their distortive character. Once samples are assessed, they cannot be used for testing, even though the sample quality is confirmed. Recently several researchers as an alternative way carry out the measurements of suction (p'_r) (sometimes it is also called "residual effective stress" in this paper) and shear wave velocity (v_s). Since these tests are of non-destructive character, the sample quality is assessed before the objective laboratory test. This paper presents the reviews of the conventional methods of assessing the sample quality based on the authors' database, in which information from various sites in the world has been accumulated. The possibility of assessing the sample quality by p'_r and v_s will be discussed.

2. REVIEWS OF THE CONVENTIONAL ASSESSMENT METHODS

2.1. UNCONFINED COMPRESSION TEST

In practice in Japan, the unconfined compression test is extensively used for the evaluation of undrained shear strength (s_u) in the total stress stability analysis. It is well known that the unconfined compression strength is very sensitive to soil disturbance because of non-confining pressure exerted on the specimen. Figures 1 and 2 show the stress–strain relation measured by the UC test, where the samples were collected by various samplers. Figure 1 presents the test results at the site of Ariake, where six different samplers were used. Detailed geometry or features of these samplers, including sampling procedures, are described, for example, by TANAKA [6]. As can be seen in figure 1, significant differences in peak strength of curves are observed. For example, the value of q_u of the sample collected by the Shelby tube is less than half of the strength of samples taken by the Sherbrooke sampler, which guarantees the best quality in this comparison study. Also it can be seen from

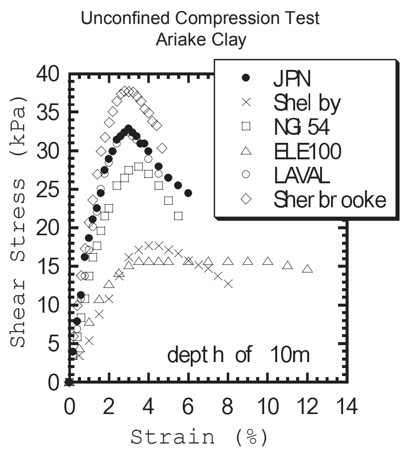

Fig. 1. Comparison of sample quality at the site of Ariake (after TANAKA [6])

figure 1 that strain at failure (ε_f) becomes great when the sample is disturbed. Inevitably, the deformation modulus, for example, E_{50}, becomes smaller for disturbed samples. However, these differences can be recognized in the samples of different quality or by referring to fundamental knowledge, for example, to the ratio of the strength to the in situ vertical effective stress, i.e., s_u/σ'_{v0}. In practical investigation, a sample is collected by a single method, hence the samples of different quality cannot be gained. Also it is very hard to judge whether the strength or Young's modulus indicates correctly their properties, or they are underestimated due to disturbance. Unlike q_u or E_{50}, which significantly vary with sites or depths, the order of ε_f may have a great potential for assessing the sample quality.

Figure 2 shows the test results from the Bothkennar site, where the Laval and Japanese (in the figure denoted as JPN) and ELE100 samplers were used. As at the site of Ariake, the performance of ELE100 is not good compared to the Laval or JPN ones. It should be stressed that ε_f for the Bothkennar clay taken by both JPN and the Laval samplers, which are considered to be high-quality samplers, is rather smaller than that for the Ariake site, although these samples are considered to have been collected under favourable conditions. Therefore, it should be kept in mind that ε_f is not a unified indicator valid for any soil, but is influenced by locality.

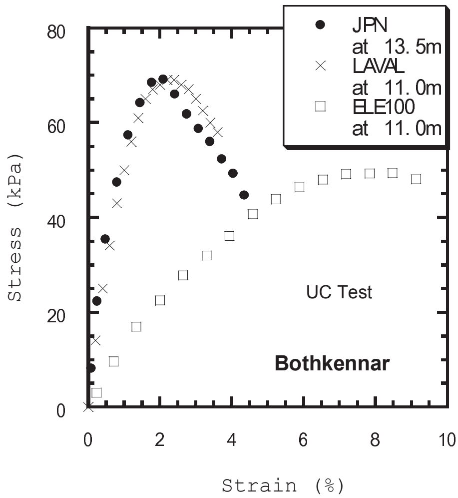

Fig. 2. Comparison of sample quality at the site of Bothkennar (after TANAKA [6])

2.2. STRESS PATH FROM TRIAXIAL TEST

It is considered that the most sophisticated method for getting a reliable stress strain behaviour is recompression method, where the specimen is consolidated under the same stress conditions as in situ conditions before sampling. Figure 3 shows the comparison of the stress paths from the Bothkennar site for the samples collected by the JPN and ELE100 samplers. A remarkable difference between samples taken by different samplers can be observed in the stress path. For JPN samples, the stress path rises linearly to the failure appearance, while for ELE100 sample, excess pore water pressure is generated in the early stage so that the shape of its stress path is somewhat round, compared with JPN one. As a result, the shear strength of ELE sample is significantly smaller than these of JPN samples, even in a recompression method. LUNNE et al. [5] proposed a correction method for undrained shear strength of poor quality samples, based on the difference in the stress paths for various sample quality.

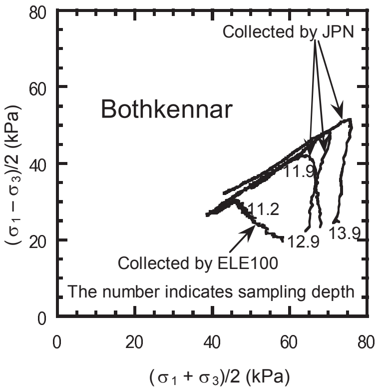

Fig. 3. Stress paths of triaxial test for Bothkennar clay (after TANAKA [6])

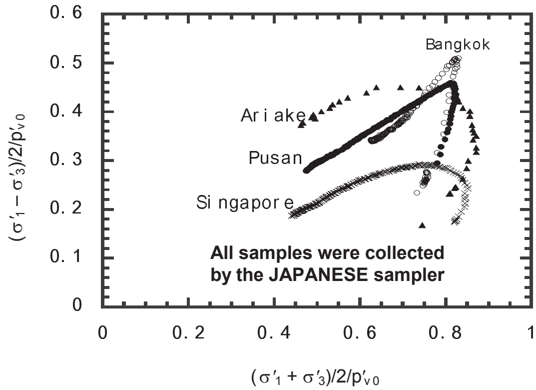

Fig. 4. Stress paths for various soils (after TANAKA [7])

Figure 4 shows the comparison of stress paths for four different clays, whose all samples are collected under the same sampling conditions, i.e., using the JPN sampler, being supervised by the first author (TANAKA [8]). The stress paths of the Bangkok and Pusan clays follow the same pattern as the high quality sample at the site of Bothkennar, as indicated in figure 3. However, there are no clear bend points in the stress paths for Ariake and Singapore. As a result, the shapes of their stress paths are apparently the same as that of the path representing a poor sample of the Bothkennar clay. It can be concluded that the assessment of the shape of stress path cannot always be applied to every kind soil. We have to consider the local difference in the soil properties.

2.3. OEDOMETER TEST

In figure 5, the curves representing the *e*–log *p* relation measured by CRS (Constant Rate Strain oedometer test) for two samples of different quality at the Bothkennar site (TANAKA [6]) are compared. As can be seen, the curve of the specimen of poor quality does not reveal a clear bend point corresponding to the pre-consolidation pressure p_c (or sometimes it is called a yield consolidation pressure). Since large strain is generated even before the appearance of p_c, large volume change is observed at the in situ effective vertical stress (σ'_{v0}). This volume change is denoted by ε_{v0} afterwards. On the other hand, for the sample collected by the JPN sampler, the point of p_c is clearly observed. When the consolidation pressure exceeds the value of p_c, large volume change is yielded so that larger compression index (C_c) for the high quality sample can be observed. Since the volume change at consolidation pressure lower than the value of p_c is small, the order of ε_{v0} is small. Using ε_{v0} or the change in void ratio to the initial void ratio, i.e., $\Delta e/e_0$, the criteria for sample quality assessment have been proposed (ANDERSEN and KOLSTAD [1], LUNNE et al. [3]).

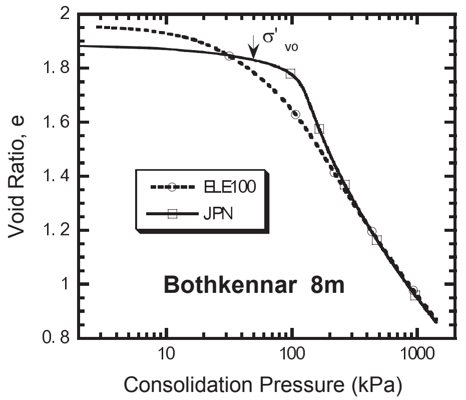

Fig. 5. e versus log p measured by CRS test for Bothkennar clay (after TANAKA [6])

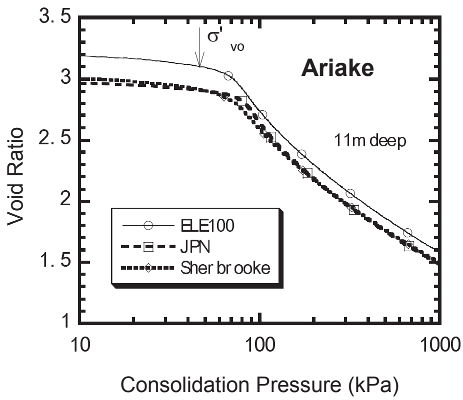

Fig. 6. e versus log p for different sample quality for Ariake clay (after TANAKA [6])

However, poor-quality samples do not always follow the same pattern as indicated in figure 5. Figure 6 shows the comparison of e–log p curve for the Ariake clay, whose three different samples were tested (TANAKA [6]). As can be seen in figure 1, the performance of the ELE100 sample is not good in the unconfined compression test. As can be seen in figure 6, however, the e–log p curve for the ELE100 sample is almost the same as those for the JPN and Sherbrooke samples. It may be anticipated that there are two types of sample disturbance: structure destruction and suction loss (to go into details, see TANAKA [6]). It is obvious that if the structure of the sample is destroyed by mechanical disturbance during the sampling process, the suction in the sample is inevitably reduced. However, even when the structure is not destroyed, suction may possibly be reduced, for example, if sand seams are in the sample. It is probable that the Ariake or Singapore clay is tuffaceous enough to preserve its structure, even though the sample is suffered from heavy mechanical disturbance, since its stress paths are round unlike the Bothkennar or Pusan clay. However, if the sample is collected in a improper way, it easily loses suction. As a result, the unconfined compression strength is reduced because of non-confining pressure.

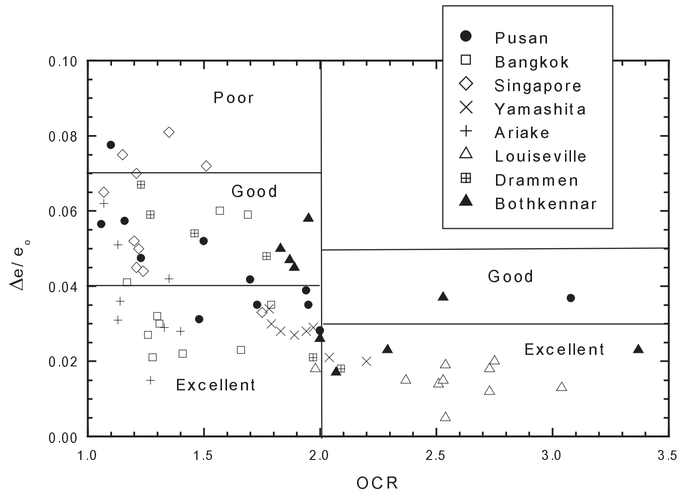

Fig. 7. $\Delta e/e_0$ for various soils (after TANAKA et al. [7])

Another difficulty in sample quality assessment using the e–log p curve from oedometer test is depicted in figure 7, where $\Delta e/e_0$ and OCR relations from authors' data base are examined with sample quality criteria proposed by LUNNE et al. [3]. All samples were collected by the JPN sampler and the sampling procedure was supervised by the first author. Although the ratios of $\Delta e/e_0$ for most samples are fallen into criteria of "excellent" or "good", some samples are classified into "poor". The causes of getting poor assessment from $\Delta e/e_0$ criteria may be due to the difficulty in oedometer testing and the fact that swelling properties vary in different soils. In the oedometer test, the soil specimen is required to set in the oedometer ring. Some disturbance is inseparably linked with this process. During the consolidation process from an initial suction to the in situ stresses in the oedometer, the effective stress in the specimen is changed. In this process, some volume change takes place, being in proportion to the constrained modulus (M), which not only may be influenced by sample quality, but also varies in each soil. Therefore, it may be concluded that there are still many obstacles for establishing the unified standard valid for any kind of soil.

3. SUCTION AND SHEAR WAVE VELOCITY

3.1. SUCTION

A soil element in the ground is subjected to σ'_{v0} in vertical direction and to σ'_{h0} in horizontal direction. When the soil is sampled to be tested in the atmosphere, the pressures exerted on the soil become zero in terms of total stress. However, negative pore water pressure remains in the sample, hence even in the unconfined compression test, the specimen is subjected to some effective stress. Under ideal conditions, sometimes called "perfect sampling", the degree of suction (p'_r) should be equal to the mean of the in situ confining pressure: i.e., $p'_m = (\sigma'_{v0} + 2\sigma'_{h0})/3$. Due to mechanical disturbance caused by sampling process or preparation for laboratory testing, p'_r is somewhat reduced compared to p'_m. The principle of the sample quality assessment using suction measurement is to compare measured suction (p'_r) to p'_m, i.e., p'_r / p'_m. Because of the difficulty in measuring σ'_{h0}, p'_r is usually compared with σ'_{v0}, i.e., p'_r / σ'_{v0}.

An example of measured p'_r is given in figure 8, where the test was conducted for the Ariake clay samples collected by six different samplers, corresponding to those in figure 1. The magnitudes of p'_r in the samples are very similar in the unconfined compression test. That is, the orders of p'_r for the Sherbrooke, Laval and JPN samples, being also characterised by high compression strength, are considerably larger than that for the Shelby tube or ELE100 samplers.

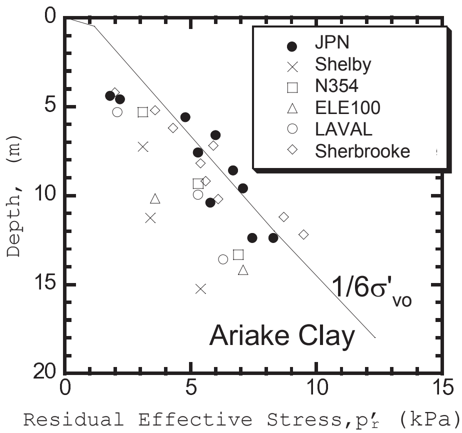

Fig. 8. Suction (residual effective stress) in samples collected by various samplers (after TANAKA [6])

Another example is the p'_r distribution in the sampling tube, as shown in figure 9. In this investigation, samples were collected by the JPN sampler with two different angles at the cutting edge, i.e., 6 and 90°. In the geometry of the JPN standard sampler, the cutting edge is 6°. For both cutting angles, in the upper and lower parts of the sampling tube, p'_r is smaller than that in the central part. This may be explained as follows: the upper part is disturbed in the drilling process, and in the lower part, some amount of vacuum is generated when the sampler is withdrawn from the ground. The edge angle affects the value of p'_r. The p'_r value for the sample collected by 90° sampler is considerably smaller than that for the sample collected by 6° one. Based on these two figures, it is possible to assess the sample quality using the suction. However, the p'_r value is not only influenced by sampling method, but it also varies, depending on the properties of soils (TANAKA and TANAKA [9]).

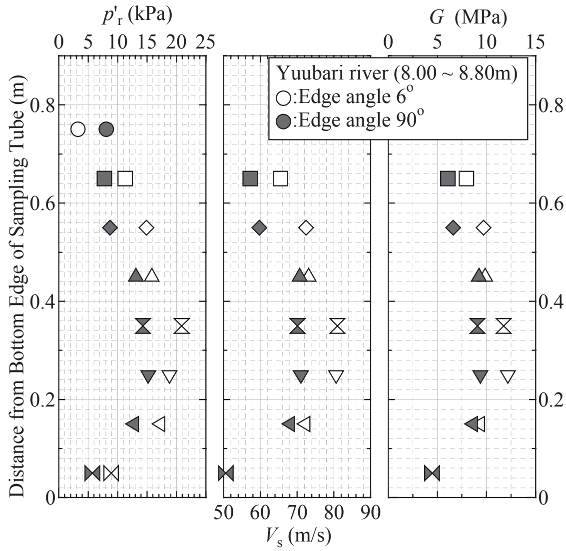

Fig. 9. Variety in suction and shear wave velocity in the sampling tube

Figure 10 shows the p'_r/σ'_{v0} ratio measured in several clays, collected by the JPN sampler. From figure 10 it can be seen that the p'_r/σ'_{v0} ratio is strongly influenced by OCR. As we mentioned earlier, p'_r is reasonably related to p'_m rather than to σ'_{v0}. It is reported that when OCR becomes larger, σ'_{h0} increases so that p'_m increases with an increase in OCR. Therefore, high p'_r/σ'_{v0} for high OCR clay is quite reasonable. It is also pointed out that at an increase in OCR a positive dilatancy is developed when specimen is sheared (HIGHT [2]). This tendency may prevent the reduction of p'_r caused by sampling soil of large OCR.

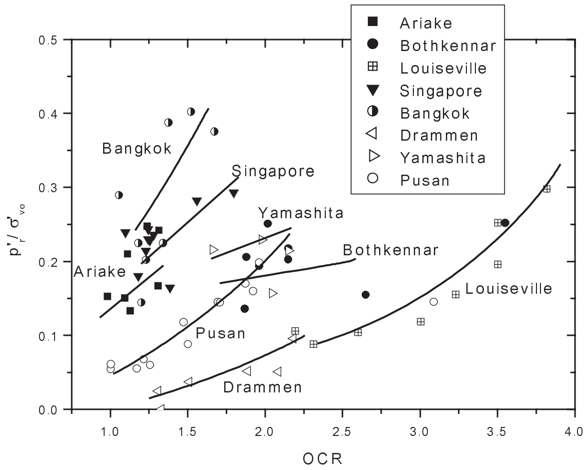

Fig. 10. The ratio of p'_r / σ'_{v0} for various soils, where all samples were collected by JPN sampler (TANAKA and TANAKA [9])

3.2. SHEAR WAVE VELOCITY

Another non-destructive method for assessing the sample quality is the measurement of the shear wave velocity v_s under unconfined stress conditions. The shear wave velocity can be measured by a pair of bender elements: one element generates the shear wave by vibrating the element and another one receives the shear wave. Sample disturbance may be evaluated by comparing the ratio of v_s measured in this way to v_s measured in situ, for example, by the seismic cone.

An example of measurement is shown on the right hand side of figure 9, where the shear modulus G is calculated from v_s:

$$G = \rho v_s^2 , \tag{1}$$

ρ being the bulk modulus of the specimen.

It can be seen from figure 9 that G or v_s is relatively small in the upper and bottom parts of the sampling tube in a way similar to the distribution of p'_r. Also it should be kept in mind that these parameters are small for the samples collected by 90° sampling tube.

3.3. RELATIONSHIP BETWEEN v_s AND p'_r

It is anticipated that there is a relationship between G and p'_r. Indeed, such a dependence can be plotted for all measured soils (figure 11), although it somewhat varies, depending on soils.

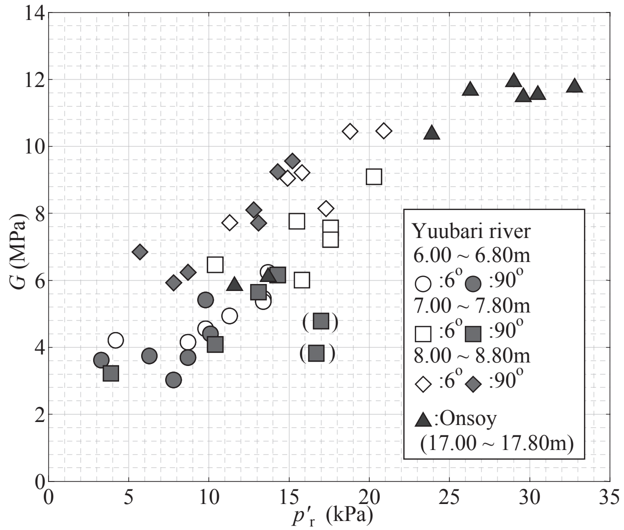

Fig. 11. Relationship between suction and shear modulus

In order to study the relationship between p'_r and G in more detail, the shear wave velocity in the Onsoy sample was measured at various confining pressure (p') in a triaxial cell. Two kinds of test were carried out, as indicated in the stress path in figure 12. Test 1: Once the specimen was consolidated in in situ stress state (the point A in figure 12), only the deviation stress was released under undrained conditions (the point B), which may correspond to "perfect sampling". Then, some cyclic deviation stresses were applied to the specimen under undrained conditions, which was intended to simulate mechanical disturbance caused by the sampling process (the points from C to H). Finally the specimen was again consolidated at in situ stress (the point I). Test 2: A specimen was first subjected to isotropic stresses, whose magnitude is equal to that of the suction pressure (denoted by "a" in figures 13 and 14). Then, the specimen was isotropically consolidated and swelled. Figure 13 shows the change in a void ratio in these tests. When the specimen was consolidated under in situ stress conditions, Δe of about 0.05 was yielded ($\Delta e/e_0$ = 0.03). At the perfect sampling as well as in the process of the cyclic loading, no volume changes took place, because they occurred under undrained conditions. It should be noted that volume changes in both tests are quite slight even at isotropic consolidation and swelling.

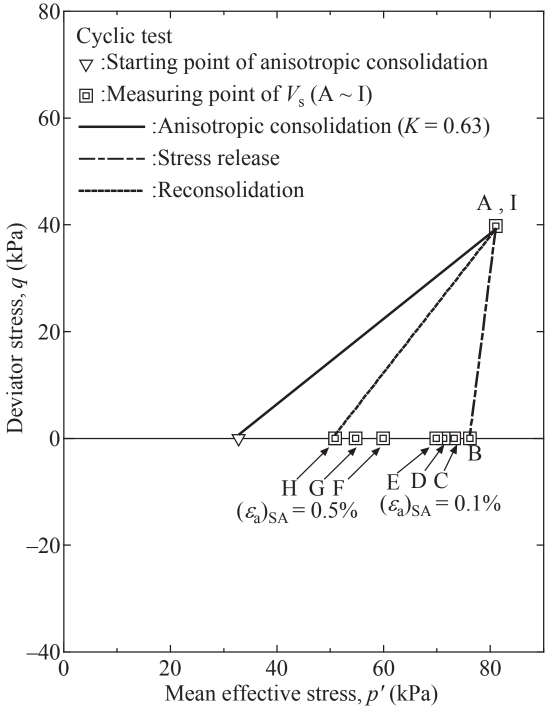

Fig. 12. Stress path for studying the relationship between p' and G

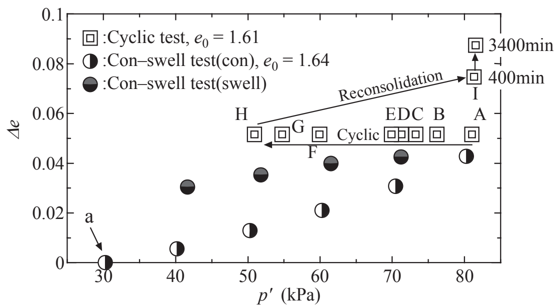

Fig. 13. Change in void ratio during triaxial test

Figure 14 shows all test results for the Onsoy clay: the specimens at various locations of the sampling tube, where v_s and p'_r were measured under unconfined stress conditions (various v_s and p'_r were due to different sample quality); the specimens subjected to cyclic stress for simulating mechanical disturbance after consolidation by in situ stresses; various isotropic stresses in both consolidation and swelling. As is shown in figure 14, there is a unique relationship obtained experimentally between p'_r and G, and this relationship can be expressed by $G = 1.99\, p'^{0.5}_r$. Many researchers have previously proposed the relationship between G and confining pressure p':

$$G = f(e)p'^n, \tag{2}$$

where $f(e)$ is a void ratio and n is an experimental constant, usually $n = 0.5$. In the relationship indicated in figure 14, the change in void ratio is so small (see figure 13) that the influence of $f(e)$ can be ignored. Therefore, the relationship measured in this study is quite reasonable, referring to the previous researches.

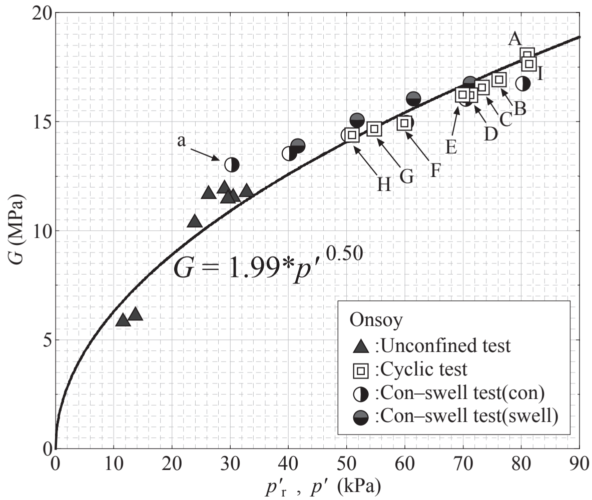

Fig. 14. Relationship between p' and G under unconfined and confined stress conditions

4. CONCLUSIONS AND PRACTICAL APPLICATION

Based on experiments and theoretical considerations, it can be conducted that measurements of suction and v_s under unconfined stress conditions are quite useful for assessing the sample quality. However, if we want to put these methods into practice, we should remember about:

1. Suction: the intensity of suction is influenced by OCR as well as by various factors, which is shown in figure 10. These factors have not yet been clearly identi-

fied. Therefore, the ratio of p'_r/σ'_{v0} cannot be used as a unique criterion for classifying the sample quality.

2. Shear wave velocity (including shear modulus): in practice, in situ measurement of v_s is still not a common investigation method, and cannot be compared with v_s measured at laboratory using the bender element. Another technical difficulty is to identify the arrival time in the measurement with the bender element. For example, in figure 14, the value of v_s after specimen consolidation by in situ stresses should be identical to the value of v_s measured in situ. According to LUNNE et al. [4], p'_r measured in situ is 32 MPa, and this value is 1.8 times larger than the value of p'_r shown in figure 14. In this study, the causes of such a large difference between two values are not identified, perhaps they arise as a result of measuring method, especially if we deal with identifying the arrival time or sample disturbance, even after a specimen consolidation due to in situ stresses.

It is required to solve the above problems which allows us to apply these methods to the assessment of sampling quality.

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