EFFECTS OF SAMPLE DISTURBANCE ON DYNAMIC PROPERTIES OF SAND

KOHJI TOKIMATSU* and YOSHINORI HOSAKA**

ABSTRACT

Laboratory tests were conducted on sand samples obtained by two different methods: in situ radial freezing which is likely to preserve the in situ dynamic soil properties, and conventional coring with a triple tube sampler. The results show that: (1) despite a relatively small difference in the drained shear strength, the undrained cyclic shear strength of the tube sample is considerably lower than that of the sample by freezing; and (2) the possible cause of this difference is a change in negative dilatancy characteristics due to sampling disturbance. Samples having dynamic characteristics similar to those of the sand by freezing were formed and tests were run on the samples to study major factors influencing sample disturbance. The test results imply that: (1) the shear stress history occurring during sampling is the primary factor reducing the undrained cyclic shear strength and modulus, whereas the reduction of confining pressure alone has negligible influence; (2) the deterioration of undrained cyclic shear strength due to sample disturbance is well correlated with a change in the elastic shear modulus; and hence (3) the degree of sample disturbance can be assessed to some extent by comparing the two elastic shear moduli measured in the laboratory and the field.

Key words: dilatancy, laboratory test, liquefaction, sample disturbance, sampling, sand, shear modulus, shear strength (IGC : D 7/D 6)

INTRODUCTION

It has generally been recognized that insertion of a tube sampler, reduction of confining pressure, and poor handling and trimming in a conventional sampling and testing procedure can induce density changes of sand and the associated rearrangement of soil grains, and as a result, the measured undrained cyclic shear strength is likely to be less than that of natural sand deposits (e.g., Mori et

al, 1978). In consequence, a more fundamental understanding of sample disturbance as well as development of a better undisturbed sampling procedure is the key issue if meaningful evaluations of liquefaction or cyclic mobility are to be made based on the laboratory test.

Seed et al (1982) made a valuable contribution to the understanding of sample disturbance based on sampling from deposits of known dynamic characteristics of sand.

* Research Associate, Tokyo Institute of Technology, Meguro-ku, Tokyo.

** Graduate Student, Tokyo Institute of Technology, Nagatsuta, Yokohama.

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Their study seems to lead to the following conclusions :

(1) A sand formed by a pluviation method such as used in the laboratory investigation is relatively insensitive to sample disturbance.

(2) "For natural deposits, however, at the same density, a similar sand is likely to have acquired considerable additional resistance to cyclic loading as a result of the effects of long term loading or sustained pressures. ... Such natural sands will therefore be much more vulnerable to a loss of strength due to sample disturbance than the relatively insensitive sand used in the laboratory investigation."

(3) For a sand sampled from a relatively dense natural deposit, "the measured resistance is likely to be less than that of the natural deposit, the difference increasing as the density increases."

It is reasonable to consider that different sampling procedures lead to a different degree of disturbance in such a way that a sand involving a large density change shows a lower strength than that with a small density change. Hence, without a means for assessing the degree of disturbance, the actual in situ characteristics cannot be correctly estimated with the current laboratory testing procedure. It is conceivable further that the degree of disturbance can be closely related to the degree of stress histories during sampling and handling. These include : (1) reduction of confining pressure, (2) shear stress history, and (3) a combination of the two. But the extent to which each of these factors can affect the dynamic characteristics is

not yet clear.

In order to improve the current knowledge for evaluating and minimizing sample disturbance, it seems therefore desirable to develop a method for estimating the degree of disturbance and to identify the major factors influencing it. The study in the following pages was conducted to investigate these points, based on the test results from two sampling methods.

SAMPLING AND SITE CHARACTERISTICS

The sampling site was located in Niigata City. A soil profile at the site is shown in Fig.1. The two sampling methods used at the site were : conventional coring with a triple tube sampler which is extensively used in the current practice to obtain "undisturbed samples," and in situ radial freezing that is considered to secure the in situ characteristics

Fig. 1. Soil profile at sampling site

Table 1. Physical properties of sands tested

	Specific gravity of solids G_s	Mean grain size D_{50} (mm)	D_{10} (mm)	Coeff. of uniformity U_c	Fines Content (%)	Maximum dry density ρ_{max} (g/cm ³)	Minimum dry density ρ_{min} (g/cm ³)	Relative density D_r (%)
Cyclic Load Testings								
FS sample	2.70	0.30	0.19	1.7	0	1.51	1.22	87
TS sample	2.71	0.31	0.20	1.7	0	1.51	1.18	72
Static Load Testings								
FS sample	2.73	0.29	0.17	1.8	0	1.52	1.22	82
TS sample	2.70	0.27	0.18	1.6	0	1.53	1.20	77
Reconstituted Sample	2.69	0.29	0.17	1.8	0	1.52	1.22	88

and hence to provide a reasonable basis for assessing how different the measured values of the other procedure are from the in situ properties. Detailed procedures of the sampling are described elsewhere (Yoshimi et al, 1984). After draining pore water, the tube samples by the coring, called TS samples, were frozen to prevent further disturbance during transportation and specimen preparation for testing. The effectiveness of this method to maintain liquefaction characteristics of clean sands was demonstrated by Singh et al (1982) and Kokusho et al (1983). The samples obtained by the in situ freezing technique, called FS samples, and TS samples were then handled in the same manner to eliminate probable effects due to difference in handling procedure.

Sands from a depth of about 9.5 m were used in this study as shown in Fig.1. The physical properties of the sands are tabulated in Table 1. The average relative density of the TS sample is about 10 percentage points lower than that of the FS sample, probably because of the dilation during the sampling. The SPT *N*-value of the sand by the Japanese trip monkey method is about 32. The shear wave velocity of the sand is 210 m/s which corresponds to an elastic shear modulus of 850 kgf/cm² (83 MPa).

CYCLIC LOADING CHARACTERISTICS OF UNDISTURBED SAMPLES

Test Apparatus and Test Procedure

Cyclic triaxial tests were conducted to compare the undrained cyclic shear strengths of the two samples obtained by the different sampling methods. A load transducer and two pairs of gap sensors were installed in the triaxial cell to measure low-amplitude shear moduli. With a similar system, Kokusho (1980) successfully measured shear moduli of sand at shear strains as low as 10⁻⁶. The samples, approx 125 mm high and 50 mm in diameter, were thawed, saturated and consolidated under a 1 kgf/cm² (98 kPa) isotropic confining pressure that is considered the vertical effective overburden pressure of the

sands in situ. Further details of the sample preparation procedure have been described by Yoshimi et al (1984).

To determine the elastic shear modulus, a non-destructive cyclic loading test was conducted just prior to the liquefaction test. In general, shear modulus in cyclic loading conditions can be given by :

$$G = \frac{1}{(1+\nu)} \frac{\sigma_d}{DA} \quad (1)$$

in which σ_d =deviator stress, DA =double amplitude of axial strain and ν =Poisson's ratio. The corresponding shear strain, γ , can be determined by :

$$\gamma = \frac{1}{2}(1+\nu)DA \quad (2)$$

In the equation, $\nu=0.5$ was assumed since the sand was saturated and the test was run under undrained conditions. After determination of the elastic shear modulus at 10⁻⁵ shear strain, hereby designated as reference shear modulus, G_r , the sample was cyclically loaded to obtain its liquefaction characteristics.

Test Results

Fig.2(a) shows the shear modulus changes with shear strain for a FS sample compared

Fig. 2. Variation of shear modulus with shear strain for sands tested

Fig. 3. Comparison of liquefaction characteristics for two different undisturbed samples (after Yoshimi et al, 1984)

with the average reference shear modulus of the TS sample. With a small standard deviation of about 15 kgf/cm^2 (1.5 MPa), the average reference shear modulus of the FS sample is 800 kgf/cm^2 (78 MPa), which appears to be consistent with the value from the shear wave velocity measurements in the field. The TS sample, in contrast, shows a significantly lower modulus.

Also shown in the figure is the attenuation curve for a sample formed by air pluviation method (PA) to the density of the FS sample but the shear modulus of the TS sample. It can be seen that the FS sample provides a considerably higher shear modulus than the other for any shear strain level. However, no difference is observed in Fig.2(b) when the shear moduli for the two samples are normalized with respect to their moduli at about 10^{-6} shear strain.

The relationships between shear stress ratio and number of cycles required to cause a $DA=5\%$ for the two samples are compared in Fig.3. The shear strength of the dense TS sample is only about 30% of the probable in situ strength of the FS sample, which shows a good agreement with the general trend of sample disturbance summarized in Introduction. This fact together with the reduction in shear modulus indicates that, while the

Fig. 4. Static strength and deformation characteristics of two different undisturbed samples

FS sample maintains the in situ characteristics, the TS sample was considerably disturbed during sampling.

STATIC STRENGTH AND DEFORMATION CHARACTERISTICS OF UNDISTURBED SAMPLES

Test Apparatus and Test Procedure

It is now generally believed that the pore pressure generation under undrained cyclic loading conditions is closely related to the volume change characteristics in drained shear. Drained triaxial shear tests were, therefore, performed to throw further light on the effect of sample disturbance. The sample size, the method of sample preparation and the confining pressure used were the same as those adopted in the cyclic loading tests. After the reference shear modulus of the sample was determined, triaxial compression or extension test was conducted at an axial strain rate of 0.2%/min while keeping the lateral pressure constant.

Test Results

The static strength and deformation characteristics of the FS and TS samples during shearing are compared in Fig. 4.

Despite the significant difference in the undrained cyclic shear strengths of the two samples, the reduction in the static shear strengths of the TS sample appears relatively small. This is probably because the static shear strength of a clean sand is related primarily to the soil density alone and relatively insensitive to a change in the soil fabric caused by sample disturbance. However, this may not be the case for sands with cohesion.

The deformation characteristics before the failure of the two samples, on the contrary, are considerably different in two points. First, the TS sample is much more contractive than the FS sample, particularly in the extension. It seems that this difference played an important role in inducing the low undrained cyclic shear strength of the TS sample, when realizing that the pore pressure generation is caused by the tendency for volume to contract in shearing, i.e., negative dilatancy characteristics. Second, the secant modulus of the TS sample is substantially

lower than that of the FS sample at any axial strain. This is consistent with the difference in the cyclic shear moduli as shown in Fig. 2(a).

DISTURBANCE OF "UNDISTURBED SAMPLE"

Although the test results are limited, the aforementioned is probably one of few attempts to investigate the effect of sample disturbance on static and dynamic loading characteristics of "undisturbed sample" with a reasonable basis for comparison. The sand, sampled from a dense natural deposit, is considered to be extremely sensitive to disturbance. Summarized herein are the main features of the tube sample compared with the probable in situ characteristics of the sample obtained by in situ freezing.

(1) The tube sample dilated by about 10 percentage points in relative density during the sampling.

(2) The reduction in the static shear strength of the tube sample is relatively small; however, the negative dilatancy characteristics and shear modulus are considerably different from the probable in situ properties.

(3) In spite of the relatively small reduction in the static strength, the reduction in the undrained cyclic shear strength of the tube sample is significant.

(4) The possible cause of this reduction can be attributed to a change in the negative dilatancy characteristics that occurred during the sampling.

PREPARATION OF SAMPLE THAT RETAINS IN SITU CHARACTERISTICS

To evaluate significant factors causing the disturbance of "undisturbed sample" described in the preceding chapter, samples having characteristics similar to those in situ were reconstituted.

Sand from the in situ frozen sample (see Table 1 for the physical properties) was first oven-dried and placed in a flask equipped with

Fig. 5. Cyclic loading characteristics of sand formed by air pluviation compared with those of TS sample

a nozzle at its opening. The flask was then inverted to allow the sand to fall from a constant height into a specimen mold. The desired density can easily be obtained with a predetermined nozzle size and height. The sample, approx 125 mm high and 50 mm in diameter, was saturated under a 0.3 kgf/cm² (30 kPa) confining pressure. The pore pressure coefficient B-value of more than 0.96 was achieved with the aid of CO₂ gas and a back pressure up to 3 kgf/cm² (300 kPa). The sample was then consolidated under an isotropic stress of 1 kgf/cm² (98 kPa). The average relative density and reference shear modulus of the samples were 84% and 530 kgf/cm² (52 MPa), respectively. Fig. 5 shows the liquefaction characteristics of the sample which coincide with those of the TS sample. The sample was then subjected to about 10 000 cycles of constant amplitude of cyclic shear stresses under drained conditions which induce a double amplitude axial strain of the order of 0.2%. The sample was consolidated for more than 8 hours before testing.

As a result of the preshearing, the average relative density and reference shear modulus of the sample increased to 88% and 800 kgf/cm² (78 MPa) which simulate the properties of the in situ frozen (FS) sample. It has been shown that an appropriate cyclic strain history lessens the tendency for volume to

Fig. 6. Static strength and deformation characteristics of reconstituted sand compared with those of FS sample

decrease in the succeeding stress applications (Seed et al, 1977). In fact, the volume change characteristics of the reconstituted

sample, which originally showed a strong tendency to contract such as that observed in the TS sample (Fig. 4), has been improved considerably and become analogous to those of the FS sample as shown in Fig. 6. The samples thus reconstituted to the in situ density and shear modulus are hereby named reconstituted samples.

EFFECT OF STRESS HISTORIES ON CYCLIC LOADING CHARACTERISTICS

"Ideal Sample"

As stated in Introduction, sample disturbance during sampling and handling can be attributed to stress histories such as: (1) reduction of confining pressure, (2) shear stress history, and (3) a combination of the two.

While most of the reconstituted samples were subjected to one of the above-mentioned stress histories before cyclic loading test, the remainder were directly tested without any of the stress histories and hence called "ideal samples." Fig. 7 shows that the "ideal samples" simulate the liquefaction characteristics of the FS sample and thereby provide a good basis for comparison.

Reduction of Confining Pressure

A sample which is recovered without any disturbance except for a removal of confining pressure is sometimes referred to as a "per-

Fig. 7. Liquefaction characteristics of reconstituted sand compared with those of FS sample

Fig. 8. Effect of reduction of confining pressure on liquefaction characteristics

fect sample." To simulate this stress history which inevitably occurs after sampling, the isotropic confining pressure of the reconstituted sample was reduced to either 0.3 kgf/cm² (30 kPa) or 0.05 kgf/cm² (5 kPa) for 4 hours. The confining pressure was then increased to 1 kgf/cm² (98 kPa) under which the sample was consolidated for at least 4 hours. After measurement of the reference shear modulus, the liquefaction characteristics were determined.

The results are compared in Fig. 8 with the strength curve for the ideal sample. The good agreement of the two results appears to confirm the previous finding by Kokusho et al (1983) that the history of stress relief alone has insignificant influence on the measured strength. Similarly, the effect of the stress reduction on the shear modulus is found negligibly small, i. e., only less than 4% reduction in the reference shear modulus.

Shear Stress History

To simulate shear stress history occurring during conventional sampling, drained compression tests were performed on the reconstituted sample. The axial stress was increased at an axial strain rate of 0.2%/min until the axial strain reached a specified maximum value, and then unloaded to the original condition. The maximum preshearing axial strains used, ϵ_{ap} , were 0.3, 0.5, 1, 2,

Fig. 9. Effect of shear stress history on liquefaction characteristics

and 3%. The change in relative density as a result of the preshearing was only 4 percentage points at the most. Undrained cyclic shear test was then performed on the sample after measurement of the reference shear modulus.

Fig. 9 shows the liquefaction characteristics of the sample along with those of the ideal sample. It seems that the strength of the presheared sample decreases with an increase in the preshearing axial strain. It is noteworthy that the samples subjected to 2 to 3% axial strain provide only about 20 to 30% of the strength of the ideal sample, showing similar characteristics of the tube (TS) sample. Equally notable is a marked reduction in the shear modulus with increasing preshearing axial strain. Thus the effect of shear stress history on sample disturbance appears significant.

Shear Stress History during Stress Reduction

Even high quality undisturbed samples, unless frozen, may be seriously disturbed during shipping, handling, and trimming, since the effective stress of the samples is extremely low. The stress history occurring in these processes can be considered a combination of stress relief and shearing. To investigate how this stress history affects the liquefaction characteristics of reconsolidated sands, two series of tests were performed as follows:

Series A—The reconstituted sample was first

subjected to a constant amplitude of cyclic shear stresses under undrained conditions until a 7.5% double amplitude axial strain developed. The sample was then consolidated to the initial confining pressure, and again subjected to cyclic shear stresses to determine its liquefaction characteristics. A similar test, called reliquefaction test, was performed by Finn et al (1970) using a simple shear test apparatus.

Series B—The confining pressure of the reconstituted sample was first reduced to 0.05 kgf/cm² (5 kPa), and a drained compression test was conducted to induce an axial strain of 1%. After the deviator stress was reduced to zero, the initial confining pressure

Fig. 10. Effect of previous liquefaction on cyclic loading characteristics

Fig. 11. Effect of shear stress history and stress reduction on liquefaction characteristics

was restored and the cyclic stress ratio to cause a $DA=5\%$ condition was determined.

The results from these series of tests are compared with that of the ideal sample in Figs. 10 and 11, from which considerable reductions in the strength and shear modulus are obvious as a result of the preshearing during stress relief. The strength of the sample is in fairly good agreement with that of the sample presheared without stress relief, confirming that the shear stress history is the major cause of the sample disturbance.

Because of low confining stresses occurring during shipping, handling, and trimming, a small degree of mechanical disturbance or even the weight of the sample itself can produce significant shear deformation, leading to a loss in undrained cyclic shear strength. To eliminate this possibility, freezing samples with care after draining is a promising means for clean sands if the sand samples have been secured without any disturbance.

SAMPLE DISTURBANCE BY PRE-SHEARING

The aforementioned results indicate that the primary factor of sample disturbance is the shear stress history during sampling and handling. Thus, the effect of shear stress on the soil properties will be investigated in more detail.

The stress ratios required to cause a 5% double amplitude axial strain in 20 cycles, R , from Fig. 9 are normalized with respect to that of the ideal sample, R_i , in Fig. 12(a) against the maximum preshearing axial strains. The stress ratio begins to decrease when the preshearing strain exceeds 0.3%. Similar studies concerning the effect of preshearing on the undrained cyclic shear strength (e.g., Ishihara and Okada, 1978; Suzuki and Toki, 1984) show a similar trend, but the effect is expressed in different forms. Although they demonstrate that a preshearing strain smaller than the critical value increases the strength of the sand formed by a pluviation method, such a strength gain appears negligibly small in Fig. 12(a) for a

Fig. 12. Effect of preshearing on dynamic properties

sand likely to exist in a natural deposit. This would seem to indicate that the effect of "small preshearing" is less significant for sands other than freshly deposited sands.

The reference shear moduli of the samples shown in Fig. 9 are normalized with respect to that of the ideal sample and shown in Fig. 12(b). The reduction in the normalized modulus becomes pronounced for a preshearing strain in excess of 0.3% whereas a preshearing strain below this critical value appears to produce little effect. With use of resonant column test apparatus, Kuribayashi et al (1975) and Yu and Richart (1984) found similar reductions in the low-amplitude shear modulus caused by shear stress history.

For comparison purposes, the volume change characteristics of the samples in preshearing is shown in Fig. 12(c). The sand contracts until the axial strain becomes about 0.3% and thereafter dilates gradually. Note that this strain amplitude corresponds reasonably well to the critical strain mentioned above. This implies that the preshearing

Fig. 13. Effect of mobilized preshearing stress ratio on dynamic properties

with dilation can cause relative movements between soil grains and thereby reduce the undrained cyclic shear strength and modulus.

Fig. 13 shows a similar relationship but against the preshearing stress ratio, $\tan\phi$, normalized with respect to the stress ratio at failure, $\tan\phi_f$. It is not until the normalized preshearing stress ratio exceeds 0.75 that both the undrained shear strength and modulus start to drop abruptly. Suzuki and Toki (1984) also indicates that the reduction of the strength becomes significant for the preshearing stress ratio greater than 0.65 to 0.75. The good agreement suggests that this trend may be general.

Another important aspect regarding the ef-

Fig. 14. Effect of preshearing on stress ratio and density

fect of preshearing is that a substantial reduction in the strength may occur without significantly changing relative density. To illustrate this in detail, the normalized stress ratios to cause a $DA=5\%$ in 20 cycles from Fig. 12(a) are plotted in Fig. 14 against relative density changes caused by preshearing. The sample disturbance effect on the stress ratio appears sensitive only to a relative density change less than 1% and then become insensitive to a further change in the density. This is probably because: only a small amount of density change by dilation can result in shear strength and soil fabric similar to those of a freshly deposited sand which is relatively insensitive to sample disturbance, and hence the effect of further disturbance on the measured strength seems insignificant. Thus maintaining the in situ soil density cannot by itself indicate the recovery of good quality undisturbed samples.

RELATIONSHIP BETWEEN SAMPLE DISTURBANCE AND ELASTIC SHEAR MODULUS

Recently, Yasuda and Yamaguchi (1984) compared laboratory-determined elastic shear moduli of sands by conventional sampling methods, G_{oL} , with those from the in situ geophysical surveys, G_{oF} , as shown in Fig.

Fig. 15. Comparison of shear moduli measured in the laboratory and the field (after Yasuda and Yamaguchi, 1984)

15. They concluded that, as a result of sample disturbance, the laboratory measurements yielded lower moduli than those measured in situ for an in situ shear modulus greater than about 500 kgf/cm² (49 MPa), and this difference increased as the shear modulus increased. It seems in general that this trend is analogous to the effect of sample disturbance on liquefaction characteristics. After reviewing previous studies on sampling disturbance, Seed et al (1982) stated that : "In the case of dense sands, block sampling techniques provide samples which are substantially less disturbed than tube samples, and further, lead to dynamic test results for moduli and resistance to pore pressure generation under cyclic loading which are usually greater than those of tube samples." Thus the effect of sample disturbance appears to act in the same direction with regard to changing both liquefaction characteristics and shear modulus in most cases. Hence there are good reasons to expect that the shear modulus can be well correlated with the degree of sample disturbance.

Based on the above consideration, the stress ratios required to cause a $DA=5\%$ in 20 cycles for the reconstituted samples are read from Figs. 7 to 11 and plotted in Fig. 16 against the reference shear modulus. There exists a well-defined trend in which the shear modulus decreases as the stress ratio decreases. This means that the greater

the degree of sample disturbance, the lower becomes the measured shear modulus. Also shown in the figure are the test results for the FS and TS samples for comparison. It is significant and remarkable that the results coincide with those for the reconstituted samples. This indicates that the degree of sample disturbance can be assessed to some extent by comparing the two elastic shear moduli measured in the laboratory and the field. It is believed that comparison of this type can be particularly effective for relatively dense sands which are likely to suffer a substantial loss in the undrained cyclic shear strength due to sample disturbance ; however, special caution and engineering judgment are crucial in the comparison since a small variation in shear modulus may lead to a relatively large change in the strength such as shown in Fig. 16.

CONCLUSIONS

The laboratory tests on sands obtained by two different sampling methods show that : (1) despite a relatively small difference in the drained shear strength, the undrained cyclic shear strength of the tube sample is considerably lower than that of the sand sampled by in situ freezing which is likely to preserve the in situ dynamic soil properties ; and (2) the possible cause of this difference is a change in negative dilatancy characteristics due to sampling disturbance. Another series of tests on samples reconstituted to have dynamic characteristics similar to those of the sand by freezing implies that : (1) the shear stress history occurring during sampling is the primary factor reducing the undrained cyclic shear strength and modulus whereas the reduction of confining pressure alone has negligible influence ; (2) the deterioration of undrained cyclic shear strength due to sample disturbance is well correlated with a change in the elastic shear modulus ; and hence (3) the degree of sample disturbance can be assessed to some extent by comparing the two elastic shear moduli measured in the laboratory and the field.

Fig. 16. Effect of sample disturbance on stress ratio and shear modulus

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