NORMALIZED BEHAVIOR OF VERY LOOSE NON-PLASTIC SOILS: EFFECTS OF FABRIC

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ABSTRACT

In order to clarify the behavior of loose sandy and non-plastic silty soils, which are the most susceptible to liquefaction, a multiple series of tests were undertaken, concentrating on the effects of fabric. For this purpose, three distinctively different specimen preparation methods were chosen, and two or three were used for each of the materials, to prepare specimens with a very loose structure.

The loosest state of packing was found to exist, for each of the preparation methods with different void ratios. In the loosest state, the normalization of the undrained stress ~ strain curves and stress paths to the initial confining pressure, can provide a meaningful interpretation of the soil behavior. This procedure is similar to the one adopted for normally consolidated clays. Regarding the effects of fabric on the undrained behavior, it was found that they are negligible up to the peak strength. However, once the shear straining reaches the state beyond the peak, the fabric becomes a very important factor governing the undrained response of non-plastic soil, which includes the minimal or residual shear strength. When the soil is largely sheared to reach the steady state, gradual remoulding erases the initial fabric and ultimate stress state is, governed by the void ratio only, once again not affected by the initial fabric.

Key words: fabric/structure of soils, liquefaction, residual strength, sandy soil, silt, triaxial compression test (IGC: D6, D3)

INTRODUCTION

It has been shown that the main features of soil response to an earthquake induced cycling loading can be observed from the behavior in undrained monotonic loading, as both the stress ~ strain relationship and stress path in a monotonic process envelope the possible cyclic ones.

In dense soils, shearing induces strain hardening and an earthquake can produce important but only limited deformations. In very loose sandy and non-plastic silty soils, on the other hand, strain softening may cause very large deformations and displacements of tens of meters or several kilometres.

In addition, behavior of very loose sandy and non-plastic silty soils changes rather drastically with small changes in void ratio. Undisturbed sampling, therefore, is quite problematic in these soils and in situ tests are very important.

Another possibility for testing includes reconstitution of the specimens in the laboratory. However, variations in the sedimentation process or specimen preparation method are known to cause significant variations in soil

response. This seriously limits the usefulness of laboratory testing.

In order to investigate the behavior of sandy, and particularly silty soils, in the extremely loose state, a multiple series of triaxial tests were made. In order to examine the effects of fabric, two or three distinctively different methods of specimen preparation were employed for each material. Materials were chosen to contain various amounts of silt, which seem to increase the contractiveness of the soil and vulnerability of the deposit to flow failure. The materials chosen contained 8% to 72% of fines (smaller than 0.074 mm). The tests and their results are presented in the following sections.

MATERIALS

Five non-plastic materials were tested ranging from fine sand to sandy silt. The grain size distribution of the materials tested is shown in Fig. 1 and their main physical properties are given in Table 1. Nevada sand was Nevada No. 120 sand from USA. Tia Juana silty sand and Lagunillas sandy silt were natural soils taken from dikes close to Lake Maracaibo in Venezuela. Dagupan silty sand was

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Fig. 1. Grain size distribution of the materials tested

Table 1.

Material name	Fines*	D_{50} (mm)	ρ_s (g/cm ³)	e_{min}^{**}	e_{max}^{**}	W_L^{**} (%)	I_P^{**}
Nevada	8%	0.1	2.67	0.511	0.887	—	—
Toyoura sand with the silt	10%	0.175	2.65	0.532	1.04	—	—
Tia Juana	12%	0.16	2.68	0.620	1.099	—	—
Dagupan	15%	0.2	2.825	0.700	1.454	—	—
Lagunillas	74%	0.05	2.69	0.766	1.389	26.9	4

* content of grains smaller than 0.074 mm.

** as defined by Japanese standards.

provided from the area liquefied during the earthquake on 16 July 1990 in Dagupan, the Philippines. Toyoura standard sand is a river sand, commercially available in Japan. The Toyoura sand was mixed with 10% of the non-plastic silt which was obtained by milling the original sand in a ball mill.

METHODS OF SPECIMEN PREPARATION

Three methods of preparation were chosen which would produce specimens with distinctively different fabric. The methods are illustrated in Fig. 2.

In the air pluviation method, dry soil is pluviated from a controlled height. With an increase in the drop height, the void ratio of the specimen increases. In order to obtain the loosest possible structure, the drop height was reduced to zero, and the funnel was used as defined by

Fig. 2. Methods of specimen preparation

Fig. 3. Stress paths and stress-strain curves for the Nevada sand specimens, prepared using the method of moist placement

the Japanese standard for the determination of the maximum void ratio. This method was named *dry deposition, DD*.

Water sedimentation, WS, similar to the method used by Baziar and Dobry (1991), followed roughly natural sedimentation in still water. For each of the four layers, de-aired water was very slowly poured into a mould, and then, using a funnel, dry soil was slowly deposited into the water. The size of its opening as well as the elevation above the water level were kept at 0.3 cm.

In *moist placement, MP*, moist soil, with a controlled uniform water content, was placed into a mould and then carefully tamped into a homogeneous and isotropic structure. Water content varied from 5% in sands to 20% in finer soils. This method is very convenient in sand testing, because it can provide specimens with a wide range of void ratios, from a minimum value, for which considerable amount of tamping energy is necessary, up to the values well above the standard minimum value, allowed by capillary forces between the soil grains. In the case of silty materials, structure can be extremely loose in such a moist state, but wetting then leads to the loss of capillary forces and a considerable decrease in volume (collapse, for example investigated by Yi, 1991).

EXPERIMENTS

A triaxial test apparatus was used with a size of specimens 5 cm in diameter and 10 cm in height. After the specimens were prepared, a small vacuum pressure of 0.02 MPa was applied to reduce disturbance during the cell installation, and, in the case of dry deposition and water sedimentation, during mould removal.

Afterwards, the specimens were saturated using carbon dioxide gas and de-aired water. Flow of both the gas

and water was controlled to be very slow, in order not to disturb the soil structure. After percolation of carbon dioxide, half an hour for clean sands to eight hours for pure silts, and de-aired water, one hour for clean sands to one day for pure silts, the *B* parameter reached a value of 0.97 or more.

Specimens were isotropically consolidated at several initial confining pressures, varying from 0.1 to 0.5 MPa. In undrained conditions, specimens were axially compressed with a constant strain rate of 0.01 to 0.03 cm/min.

Fig. 4. Relationships of mean effective stress and void ratio for Nevada sand prepared using the method of moist placement

EXPERIMENTAL RESULTS

Varying Initial Void Ratio

Sandy soils can be prepared simply into various void ratios and consequent compression into various p', e states. A set of specimens with different void ratio was prepared from Nevada sand using the method of moist placement, and consolidated at the confining pressure of 0.3 MPa. The resulting stress paths and stress-strain curves are shown in Fig. 3.

For void ratios up to about 0.8, there was no decrease in the deviator stress, q , it increased monotonously until the end of the tests. The mean effective stress, p' , however, in both tests showed first a decrease and then an increase. This change in behavior, with important consequences on further soil response, is known as the *phase transformation*.

With an increase in void ratio, e , deviator stress, q , increased more slowly, and for void ratios from 0.82 to 0.85, after reaching its peak at approximately 1% of axial strain, it decreased. The mean effective stress at the peak point, p'_p , achieved a value of 0.6 of the initial value, p'_c , and remained constant for all the void ratios. Thereafter, both p' and q decreased, until their minimum, which corresponded to the sharp bend in the stress paths and to the very large expanse of the stress-strain curves. The minimum, and the phase transformation, occurred at an axial strain of 12% to 15%, after which both p' and q increased further to become almost constant again at the end of the tests at an axial strain of approximately 30%.

For void ratios above 0.88, values of p' and q continued to decrease to zero, and there was no increase in p' or q recorded afterwards. For such a soil element it is usually said that it is of *zero residual strength*.

Since no shear band occurred and the specimen shape was almost cylindrical during all the tests, it is believed that the soil structure remained homogeneous and, therefore, in the final state, stresses as well as volume and strain rate could be considered constant. Such a state is commonly named the *steady state of deformation*, particularly in references in the literature on liquefaction and stability analysis (Poulos, 1988). This state also corresponds to the *critical state* as defined in the Critical State Soil Mechanics, CSSM. The best name, however, may be the *ultimate state* (Poorooshasb, 1989). Before this state was developed, a similar state existed temporarily, when the deviator stress and mean effective stress were at their minimum and, for some time, almost constant as well as volume and strain rate were. This state is called the *quasi-steady state* (Alarcon-Guzman, Leonards and Chameau, 1988) for its similarity to the ultimate, steady state, and for its transient nature.

In p', e space, as shown in Fig. 4, the points corresponding to quasi-steady state, described with p', e , exist on the line named the *quasi-steady state line*, *QSSL*. It is shown that the quasi-steady state line is unique for one material and one method of preparation (Ishihara, 1993 and Verdugo, 1992, for Toyoura sand and moist tamping). The ultimate points, or the points at the steady state, exist on another line named the *steady state line*, *SSL*. The quasi-steady state points and steady state points in p', q plane exist on a straight line with a slope M , as shown in Fig. 3.

The compression lines, as well as the quasi-steady state and steady state lines for Nevada sand, like those of other sandy soils, are of rather gentle slope. This coincides with the high sensitivity of their behavior on the value of the void ratio. Therefore the range in the void ratio from the start of flow to the occurrence of the zero

Fig. 5. Stress paths of specimens of Toyoura sand with 10% silt, prepared using the method of moist placement, with zero or near-zero residual strength-normalized to initial confining pressure

Fig. 6. Quasi-steady state line and the initial and final states for the tests shown in Fig. 5. Thin horizontal lines show the stress paths

residual strength is as small as 0.8 to 0.88. This range should be compared with the void ratio of the loosest specimens. With further increase in void ratio, the residual strength, being always zero, is reached at a smaller axial strain. However, as can be seen for the two loosest specimens, above some threshold state, stress paths practically coincide although the values of void ratio are as different as 0.908 and 0.956.

Toyoura sand with 10% silt is another material which was prepared using the method of moist placement, and tested at various void ratios. For specimens which had very small or zero residual strength, stress paths are shown in Fig. 5. In displaying the data, shear stress, q , and mean effective stress, p' , are normalized to the consolidation confining pressure, p'_c . Although both the void ratio and initial confining pressure varied widely, the normalized stress paths are shown to be almost coincident. The initial states of the specimens are shown in the p', e diagram in Fig. 6, together with the quasi-steady state line.

These results suggest the existence of the *loosest state* in non-plastic soils. In the case of the methods of dry deposition and water sedimentation, the loosest state was clearly defined by the technical details, reducing the drop height and velocity. But even for the method of moist placement, where it was technically possible to produce extremely loose specimens, the loosest state can be defined as that with the lowest stress path.

EXPERIMENTAL RESULTS

Specimens with Various Fabrics

In addition to the method of moist placement, specimens of Nevada sand were prepared using the method of dry deposition. From the series of specimens, two were chosen, which were prepared with the two different methods, but into the same initial p', e state. Their stress

Fig. 7. Stress paths of the two specimens of Nevada sand, prepared using two different methods, with the same void ratio

paths are compared in Fig. 7. The moist placed specimen indicated a behavior without, and the dry deposited one with flow failure. This significant difference proves once again the important effects of fabric on the behavior of soil. For the two methods of preparation, Fig. 8 shows the p', e points at the quasi-steady state and at the end of each test. It is obvious that the two fabrics produce two distinct quasi-steady state lines. The steady state line, however, seems to be unique for the two fabrics.

EXPERIMENTAL RESULTS

The Loosest State

Considering the sensitivity of the behavior of non-plastic soils to changes in void ratio, it may be interesting to concentrate on the loosest state of soil and the corresponding peak and residual strengths. These are the minimal possible values of the peak and residual strengths at a given pressure.

The importance of fabric effects, however, implies that the behavior in the loosest state is also influenced by fabric. This is why a series of materials was prepared into the loosest state, using different preparation methods. In each set, specimens were approximately of the same void ratio before and after saturation. For each set of specimens from the same material and with the same method of specimen preparation, therefore, the compression lines formed practically a unique compression line. It is called the *initial compression line, ICL*, because it is related to the loosest state for each material and fabric.

For Lagunillas sandy silt, prepared using the moist placement, dry deposition and water sedimentation methods, the initial p', e states, after consolidation, are indicated in Fig. 9. The initial compression lines for the three fabrics are distinctly different.

Fig. 8. Quasi-steady and steady state lines of Nevada sand and the two methods of specimen preparation

Fig. 9. Initial compression lines of Lagunillas sandy silt, corresponding to the three methods of specimen preparation

For each of these three sets of experiments, stress paths and stress~strain curves are shown in Figs. 10, 11 and 12. For the moist placed specimens, the deviator stress reached its peak at an axial strain of approximately 1%, and then decreased until the end of loading at 25% to a very small residual value. In the case of the dry deposited specimens the peak was also reached at a strain of approximately 1%, and then the quasi-steady state at 5 to 10%. In the case of the water deposited specimens, the peak was reached again at 1%, and then the quasi-steady state at approximately 3%, followed by a much more significant increase in the deviator stress. The three different fabrics, obviously, produced very different soil behavior. This can be seen also in the p', e space in Fig. 13, where the points at the quasi-steady state are presented. The three distinctive quasi-steady state lines were achieved by the three sets of specimens prepared in the three different ways.

Looking back at the stress paths and stress~strain curves of Lagunillas, for each of these three sets of experiments separately, one more common characteristic can be noted among the different fabrics: the similarity of the stresses during the shear process. In each set of the tests, both the peak and quasi-steady state were always reached at almost the same axial strain, and in all cases, the deviator stress and mean effective stress were similar. To confirm this finding, both the stress paths and stress~strain curves were normalized to the initial confining pressure.

NORMALIZED BEHAVIOR AND EFFECTS OF FABRIC

For Lagunillas sandy silt, prepared in the loosest state as defined previously, using the three different methods, the stress paths and stress~strain curves normalized to

Fig. 10. Stress paths and stress~strain curves of the specimens of Lagunillas sandy silt, prepared using the method of moist placement in the loosest state

Fig. 11. Stress paths and stress~strain curves of the specimens of Lagunillas sandy silt, prepared using the method of dry deposition in the loosest state

Fig. 12. Stress paths and stress~strain curves of the specimens of Lagunillas sandy silt, prepared using the method of water sedimentation in the loosest state

Fig. 13. Initial compression lines and quasi-steady lines of Lagunillas sandy silt, prepared using the three methods of specimen preparation in the loosest state

the initial confining pressure are shown in Figs. 14, 15 and 16 for the moist placed, dry deposited and water sedimented specimens respectively. In all three cases, the normalized stress paths and stress~strain curves were found to be practically identical approximately up to the quasi-steady state. At higher strains, however, the stresses diverge, meaning that this normalization has no validity for the steady or ultimate state of non-plastic materials.

The same feature can be seen for the other two materials: Figs. 17 and 18 show the normalized stress paths and stress~strain curves for Dagupan silty sand prepared in the loosest state with the methods of the moist placement and dry deposition respectively, and Figs. 20 and 21 for Tia Juana silty sand prepared in the loosest state with the dry deposition and water sedimentation. In all cases, for each set of specimens prepared from the same material and using the same method of preparation, but into the loosest state, the stress paths and stress~strain relationships, when normalized to the initial confining pressure, were approximately identical up to the point where the quasi-steady state was developed.

One of the consequences of this feature is the proportionality of the stresses at the quasi-steady state and in the initial state. In the $\log p', e$ plot, therefore, as can be seen in Fig. 13 for Lagunillas, the quasi-steady state lines are parallel to the initial compression lines for each distinctive fabric. The same can be seen in Figs. 19 and 22, where the initial and quasi-steady state, as well as the ICL and QSSL are shown for Dagupan and Tia Juana specimens.

Fig. 14. Stress paths and stress~strain curves of Lagunillas sandy silt, prepared using the method of moist placement in the loosest state, normalized to the initial confining pressure

Fig. 15. Stress paths and stress~strain curves of Lagunillas sandy silt, prepared using the method of dry deposition in the loosest state, normalized to the initial confining pressure

Fig. 16. Stress paths and stress~strain curves of Lagunillas sandy silt, prepared using the method of water sedimentation in the loosest state, normalized to the initial confining pressure

Fig. 17. Stress paths and stress-strain curves of Dagupan silty sand, prepared using the method of moist placement in the loosest state, normalized to the initial confining pressure

Fig. 18. Stress paths and stress-strain curves of Dagupan silty sand, prepared using the method of dry deposition in the loosest state, normalized to the initial confining pressure

Fig. 19. Initial compression lines and quasi-steady lines of Dagupan silty sand, prepared using two methods of specimen preparation, moist placement and dry deposition, in the loosest state

Fig. 20. Stress paths and stress-strain curves of Tia Juana silty sand, prepared using the method of dry deposition in the loosest state, normalized to the initial confining pressure

Fig. 21. Stress paths and stress-strain curves of Tia Juana silty sand, prepared using the method of water sedimentation in the loosest state, normalized to the initial confining pressure

For Lagunillas, the representative curves corresponding to each of the three methods of preparation are shown in Fig. 23. The three sets of curves corresponding to the three loosest states seem to exhibit similar behavior at the early stage of the shear strain application. They almost coincide up to the peak of the deviator stress. However, the curves diverge afterwards and show that the residual strength depends significantly on the soil fabric.

The same data processing was also made for Dagupan as shown in Fig. 24. Again, the representative normalized curves almost coincide up to the peak strength approximately, and then diverge when they reach the quasi-steady state. In the case of Tia Juana, because of the scat-

ter in the stress paths and stress~strain curves corresponding to the water sedimented specimens, the two pairs of curves are chosen which coincide up to the peak point and shown in Fig. 25. It is obvious that their minima, during the same time period, differ.

These results indicate that the method of preparation, or the way of sedimentation, has an important influence on both the void ratio and response of soil. In the loosest state, however, the behavior is quite similar: up to the peak strength for one material, and almost all the way up to the residual strength for one material with the same fabric.

Fig. 22. Initial compression lines and quasi-steady lines of Tia Juana silty sand, prepared using two methods of specimen preparation, dry deposition and water sedimentation, in the loosest state

Fig. 23. Representative normalized stress paths and stress~strain curves of Lagunillas sandy silt prepared using the three methods of specimen preparation, in the loosest state

Undrained behavior is rather similar for the very loose non-plastic materials and for the normally consolidated clays. In case of the normally consolidated clays, the critical state coincided with the peak deviator stress, and all the way up to this state the stress paths for different pressures are quite similar. In addition, due to the presence of the plate like particles, shearing mode changes from turbulent to sliding, and a failure surface develops causing a decrease in shear stresses to their minimum, or the residual strength, at large displacements.

Loose non-plastic materials can remain in a homogeneous stress state even after both the peak strength and the minimum strength are reached. The similarity of the stress paths for this case, however, stops approximately at the minimal point.

Fig. 24. Representative normalized stress paths and stress~strain curves of Dagupan silty sand, prepared using two methods of specimen preparation, moist placement and dry deposition, in the loosest state

Fig. 25. Representative normalized stress paths and stress~strain curves of Tia Juana silty sand, prepared using two methods of specimen preparation, dry deposition and water sedimentation, in the loosest state

CONCLUSIONS

Sandy soils can be prepared relatively easily into various void ratios. The method of moist placement particularly can produce very loose structures of sandy soils, much looser than defined by the standard for the maximum void ratio. Therefore it was generally assumed that there is no upper boundary in void ratio of sandy soils.

The tests on Nevada sand and Toyoura sand with 10% silt have clearly shown that, in spite of this, it is possible to detect the lowest peak strength of sandy and silty non-plastic soils and that the stress paths are virtually equal for the void ratio above some threshold. This is how the loosest state is defined.

This fact could allow estimation of the lower boundary of the deviator stress and strength in the laboratory if it were not for the effects of fabric. It is very well known, however, that different sedimentation processes or specimen preparation methods create various fabrics and cause important variations in the soil response.

In order to investigate the effects of fabric on the soil behavior in a very loose state, a series of triaxial tests were performed on three silty soils using two or three distinctively different methods of specimen preparation. With each of the methods, a series of specimens were prepared into the loosest state and consolidated to isotropic confining pressures ranging from about 0.1 to 0.5 MPa. The initial compression line, the stress~void ratio path of specimens in the loosest state, was found to depend significantly on the soil fabric.

For each of the series of specimens prepared with identical method, it was found that both the stress~strain curves and stress paths normalized to the initial confining pressure practically coincide. In other words, the shapes of the stress~strain curves and stress paths do not change significantly with the initial confining pressure in the loosest state of soil approximately up to the quasi-steady state.

In addition, all the specimens of the same material prepared using various methods have their normalized stress~strain curves and stress paths almost identical up to the peak strength. This means that the minimum peak strength of soil is practically independent of the fabric. The results presented suggest that if the loosest state can be produced in the laboratory with several methods of specimen preparation, the peak strength determined will be the lowest boundary of the possible peak strength in situ.

Once the stress state goes beyond the peak, however, the effect of the preparation method is manifested and the normalized residual strength varies with the soil fabric.

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NOTATION

e	void ratio
p'	mean effective stress
p'_c	mean effective stress at consolidation
p'_p	mean effective stress at the peak of deviator stress
q	deviator stress
DD	method of specimen preparation: dry deposition
ICL	initial compression line, the stress~void ratio path followed by the soil elements in the loosest state
MP	method of specimen preparation: moist placement
QSSL	quasi-steady state line
SSL	steady state line
WS	method of specimen preparation: water sedimentation

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