Undrained behaviour of silt

Le comportement en non-drainé de la vase

Shaoli Yang – *Ocean University of Qingdao, Qingdao, People's Republic of China, now at Norwegian University of Science and Technology, Trondheim, Norway*
Rolf Sandven – *Norwegian University of Science and Technology, Trondheim, Norway*
Lars Grande – *Norwegian University of Science and Technology, Trondheim, Norway*

ABSTRACT: In this study, the undrained behaviour of silt under low stress level is investigated. An effective preparation method for built-in silt samples in the triaxial test was first developed. By triaxial testing of samples at low confining pressures it was found that silt easily loses stability and liquefies. Loose silt may show temporary liquefaction under static loading, and develop full liquefaction under cyclic loading. The most important influencing factors on the silt behaviour are porosity, confining pressure, consolidation state, cyclic loading level and number of cycles. The maximum obtainable shear stress is primarily a function of the confining pressure and the internal frictional angle. The actual structure of the silt material is the key to control its behaviour.

RÉSUMÉ: Dans cette étude, le comportement en non-drainé de la vase sous faible pression a été étudié. Une méthode de préparation efficace pour l'encastrement des échantillons de vase pour l'éssai triaxial a été dans un premier temps développé. Lors de léssai triaxial à faible pression de confinement, il a été constaté que les vases perdaient facilement leur stabilité et se liquéficient. La vase lâche peut montrer une liquéfaction temporaire sous un chargement statique et développer une liquéfaction totale sous un chargement cyclique. Les plus importants facteurs influensant le comportement de la vase sont la porosité, le pression de confinement, l'état de consolidation, le niveau de chargement cyclique et la nombre de cycles. Le maximum que l'on peut obtenir des contraintes de cisaillement est principalement fonction des pressions de confinement et de l'angle de frottement interne. L'actuelle structure du matériau silteuse est la clef du contrôle de son comportement.

1 INTRODUCTION

In those parts of the world which have experienced glaciation or alluviation, silty soils are widespread. The Quaternary period appears to be a particularly silt-rich period due to tectonic and glacial activity. Such deposits include the alluvial soils of north India, the loess deposits along rivers in central Asia, the great loess deposits of North China and North Africa, calcareous silts on the north west shelf of Australia (Fahey et al, 1999) and the Mississippi loess in North America.

About 80% of littoral areas in the world are covered by surface sediments, such as sandy and silty soils, which may be susceptible to liquefaction (Brandes, 1999). Silts are typically found in the shallow waters of the continental shelves and coastal regions, where it has presented formidable foundation engineering challenges (Murff, 1987). The sediments are often in a state of low confining stresses, which emphasize the problems.

Instability phenomena, such as liquefaction, is usually related to the response of silt under a certain kind of loading (Ishihara, 1985; Yang et al, 1995). In Northern Europe, such as northern Sweden, Finland and Norway, silty deposits are often exposed to geotechnical hazards such as flowslides and extensive surface erosion.

1.1 *Engineering problems of silty soils*

Liquefaction of saturated soil is considered to be a key factor causing failure of high dams, soil structures, slopes, offshore and onshore foundations. With respect to granular soils, much of the previous research has been focusing on behaviour of clean sands. The geotechnical properties and behaviour of such materials have been studied extensively both in laboratory and field conditions. Natural soils may however contain a significant amount of fines, which can cause instability phenomena to occur. The examples of such geotechnical phenomena are numerous, and a few of them are mentioned below. The slide in the lower San Fernando Dam, California, in 1971 developed in soil composed of approximately equal amounts of silt and sand (Ishihara, 1993). The Nerlerk berm liquefaction slides in Canada in 1983 similarly occurred in sand with a high silt content (Sladen et al, 1985). The post earthquake failure analysis of an hydraulic fill indicated that partial liquefaction occurred in the silty sand layer in the earthquake of Chile in 1985 (Poran, 1985). Liquefaction occurred in silty sand and sandy silt in the 1988 Saguenay earthquake in Quebec (Troncoso, 1988) and the 1987 Superstition Hills earthquake in California (Tuttle et al, 1988). Finally, there were clear evidences that silts liquefied under severe waves in the Yellow River subaqueous delta in China. Problems and failure indications such as tilt of offshore structures, seafloor slides and pits have been attributed to the liquefaction of saturated sandy silts and silty sands (Chen et al 1991, Feng 1992, Zhang 1993 and Yang, 1995).

1.2 *Previous study on behavior of silt*

The principal behaviour of sands and clays have been extensively studied and described over the years. However, the behaviour of silt and silty soils has been paid less attention until recent years. Lacasse and Nadim (1994) proposed that one of the most relevant and urgent issues in the specific geotechnical engineering field is to develop data describing the static and cyclic behaviour of silts and silty sands.

Since silty soils may range in composition from silty sands to clayey silts, the behaviour of silty soils may be difficult to judge a priori. A clean silt will have its own characteristic properties which only can be revealed by extensive testing. For example, a silt may appear as very stiff in a dried state, whereas it loses strength quickly when submerged into water.

An important reason for the deficient studies of silt behaviour in the laboratory is the difficulties in retrieving undisturbed samples. Even with reconstituted samples it will be difficult to prepare samples with a structure similar to the in-situ conditions. Despite of these difficulties, we still need to obtain systematic knowledge of the properties of silty soils under various loading conditions to meet the requirements from engineering practice.

Penman (1953) may have been the first to study silt behaviour extensively under drained and undrained conditions by triaxial testing. He introduced a method of vacuum and suction treatment on a silt slurry for preparation of samples. Nikhilesh et al (1976) tested compacted silt samples to study the strain rate behaviour of dense silt. It was concluded that the strain rate does have an effect on the strength of soil. As a result of their study, strain rates between 2 and 5 %/hour were recommended. Nacci et al (1976) devised a technique for the preparation of specimens of loose, layered silts. The sample preparation procedure included initial sedimentation, consolidation under small load increments and finally freezing. The obtained samples could duplicate the in-situ varved structure and index properties of the natural silt deposit.

Later on, Yu (1993) used a similar technique to study silt behaviour in the laboratory, proving that this is an effective way to prepare silt samples.

Recently, several researchers have paid much attention to the behaviour of sand containing different amount of silt. The results of these investigations are however somewhat contradictory (Pitman et al, 1994; Thevanayagam, 1997; Lade et al, 1997; Amini et al, 2000).

In coastal areas, the soils below the submerged ocean floor is usually at a low pressure level. Limited research work seems to be available, addressing the behaviour of silt under low stress level. This was the main scope of the study reported herein.

2 INDEX PROPERTIES OF THE ISVA SILT MATERIAL

The most important index properties of the ISVA silt material used in this study are summarized below:

- Maximum void ratio: $e_{max} = 1,22$
- Maximum porosity: $n_{max} = 55.0$ %
- Minimum void ratio: $e_{min} = 0.69$
- Minimum porosity: $n_{min} = 40,8$ %
- Density of solids: $\rho_s = 2.803$ g/cm^3

The grain size distribution curve is shown in Figure 1, the silt having a uniformity coefficient $C_u = 5.4$.

3 SAMPLE PREPARATION METHOD

As indicated in the previous section, it is very difficult to reconstitute silt samples in the laboratory, partly due to the susceptibility of the material to the water content. According to a Standard Proctor test, with the water content close to the optimum water content (16%) on the wet side, the sample can barely stand by itself.

There are principally three methods to prepare silt samples for tests in the laboratory. One method is to use compaction, but samples prepared using this method are generally not uniform. In addition, high water content cannot be obtained due to the water susceptibility. An improved compaction procedure using undercompaction has been developed for sand (Ladd, 1978), and may also be applicable for some silts. The second method is to prepare silt samples by sedimention of the grains, and afterwards apply a small loading on the sedimented sample to obtain the wanted porosity. This method is suitable for preparation of a homogenous sample with a moderately high water content. The last method is similar to the second one, but entails laboratory freezing to obtain a silt sample which can be handled without densification or other disturbance. There could however be some expansion of saturated samples during freezing.

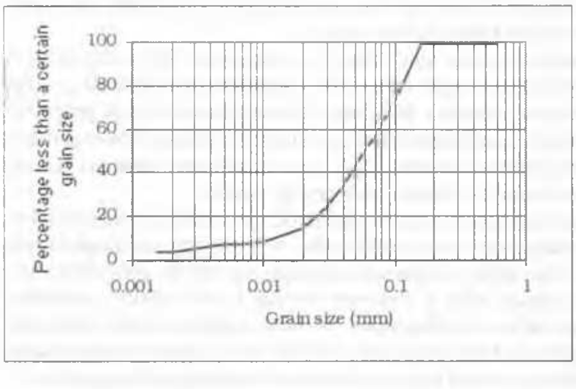

Figure 1. Grain size distribution curve of silt

In order to get good quality sample in the laboratory and simulate in-situ material structure as good as possible, an improved method based on the second one was used in the sample preparation in the study herein. First, a silt slurry at a water content of 30% is made by mixing dried silt and distilled water. This sample is left overnight to make the sample saturate as much as possible. The procedure is described in the following:

- A split mould with a rubber membrane mounted inside is installed on the pedestal of the triaxial equipment, a porous stone was put directly on the pedestal.
- Entrapped air between the membrane and the split mold is removed by vacuum treatment. Then, an additional cylinder, with inner diameter equal to the sample diameter and height of about 20 cm, is fixed on the split mould.
- Distilled water is poured into the mould before the silt slurry is introduced through a funnel. This yields a sedimentation process close to the natural conditions.
- In order to accelerate the consolidation process and make the sample stiff enough for subsequent preparation, a deadweight of 0.3 kg/cm^2 is applied to the sample using a special designed piston. Two-way drainage was allowed during consolidation.

4 RESULTS FROM CCV TRIAXIAL TESTS

A consolidated, constant volume (CCV) triaxial test procedure was used for static shear testing of the silt samples. This procedure simulates perfect undrained conditions for a soil sample.

In the study reported herein, silt samples with initial porosity of about 45% were first isotropically consolidated to various confining pressures of 10 kPa, 30 kPa, 100 kPa and 200 kPa. After completed consolidation the samples were sheared under strain controlled condition. Generally speaking, strain rate does have an effect on the strength characteristics of silt (Nikhilesh et al, 1976). In an undrained test, a reasonable choice of the strain rate must be based on the equalization of the pore pressures developed in the sample. In this study, the strain rate during shearing was selected at 2 %/hour, which was proved to be adequate for the tested material.

According to the test results in Figure 2, the confining pressure has, as expected, a great influence on the shear strength of the silt. The larger the confining pressure, the larger the shear stress. The silt samples do not reach a typical peak shear stress, even for axial strains exceeding 10 %. The undrained behaviour of silt shows a pattern of strain hardening, both for low and high confining pressure.

According to Figure 3, it is seen that the silt has contractive and dilative failure characteristics under low and high confining pressure, respectively. The effective stress paths of four tests are shown in Figure 4. The critical state line, which has been preferably called the characteristic line or the phase transformation line, is defined as the line where the effective stress path is reached with no change of pore pressure in undrained condition, or no volume change in drained condition. Figure 4 displays that the stress path reaches the critical state line then turns and moves

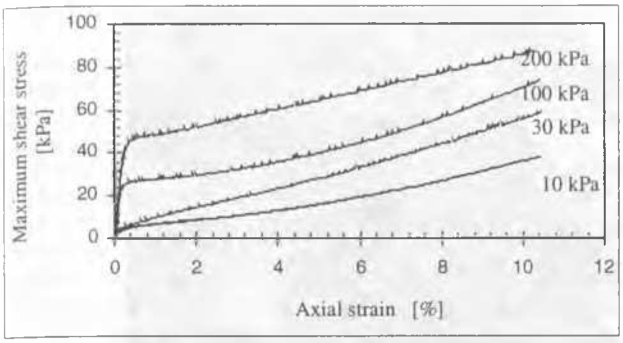

Figure 2. Maximum shear stress and axial strain curves of CCV tests

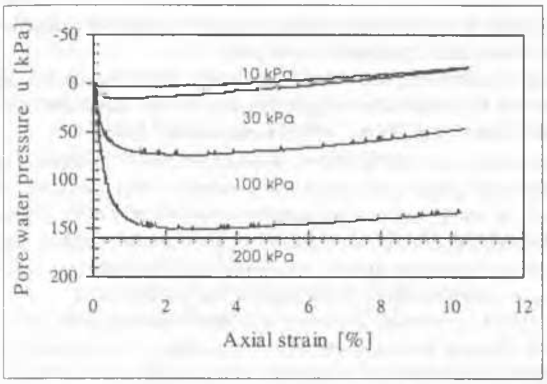

Figure 3. Pore water pressure and axial strain curves from CCV triaxial tests

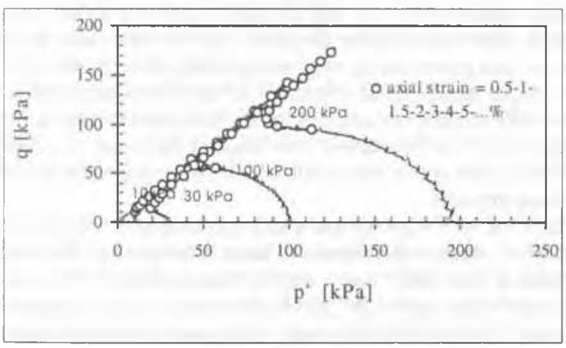

Figure 4. Stress paths from CCV triaxial tests

along the failure line. Before the stress path reaches the phase transformation line, the behaviour of silt resembles that of a clay. The properties of silt could hence be simulated according to the models developed for clay. However properties of silt after dilation should be simulated according to appropriate models for sand, in which dilative behaviour should be considered. Silt is hence a kind of material with both contractive and dilative characteristics, depending on the actual stress and strain level.

5 RESULTS FROM CIU TRIAXIAL TESTS

Consolidated isotropic undrained (CIU) triaxial tests have also been carried out as a part of the study.

In all CIU tests, a back pressure of 500 kPa was applied to the samples. The corresponding B - value was equal to or exceeded 0.97, with the porosity before shearing being about 44 %.

Confining pressures of 10, 30 and 100 kPa were used during CIU tests. However, it was not possible to run CIU tests on samples with high back pressure under the very low confining pressure of 10 kPa due to limitations in the test equipment.

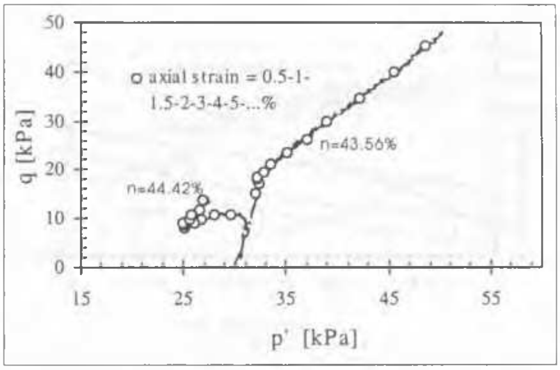

Figure 5. Stress paths from CIU triaxial tests under confining pressure of 30 kPa

According to the study of Yamamuro et al (1997), one may obtain both static and temporary liquefaction in undrained triaxial tests on loose sands. Temporary liquefaction is defined as the condition where the deviator stress first shows an initial peak, after which it declines to a minimum value. The results obtained for one of the samples at 30 kPa confining pressure in Figure 5 is very similar to the condition described as temporary liquefaction. The shear stress increased until a maximum peak value was obtained, after which it decreased very slowly until a transitional point was reached. The decrease of shear stress was caused by the decrease of effective stress, following the rapid increase of pore pressure. At the beginning of the CIU test, the silt sample contracts, but the tendency of contraction stopped after a small axial strain was reached. A dilative tendency then becomes more and more exposed. The shear stress also begins to increase due to the dilative behavior.

The initial porosity is one important parameter to indicate the behaviour of silt as shown in Figure 5.

According to CIU and CCV test results, the undrained shear strength of silt under a certain confining pressure is about the same in these two kind of test procedures. According to Janbu (1985), the undrained shear strength of a fine-grained material can be approximated by the semi-theoretical relationship:

$$\tau_{max} = s_u \approx 1/2\ (\sigma_c' + a)\sin\phi$$

where:

s_u = shear strength
σ_c = maximum previous consolidation stress
a = Coulombian attraction
ϕ = internal friction angle

From the results in this study, the shear stress ratio (τ_{max}/σ_c') can also be evaluated through this formula, see Table 1.

6 INFLUENCE OF PRECONSOLIDATION ON THE BEHAVIOUR OF SILT

In situ, a silt deposit may be in an overconsolidated state, and the undrained strength should hence be related to this stress situation. One CCV test was run on an artificially overconsolidated sample, its overconsolidation ratio being about 6.5. The

Table 1. Undrained shear strength of silt

σ_c'	CIU			CCV		
	τ_{max}	τ_{max}/σ_c'	n (%)	τ_{max}	τ_{max}/σ_c'	n (%)
30	7	0.25	43.6	7	0.23	44.5
100	28	0.28	43.4	27	0.27	44.2
200				47	0.24	43.8

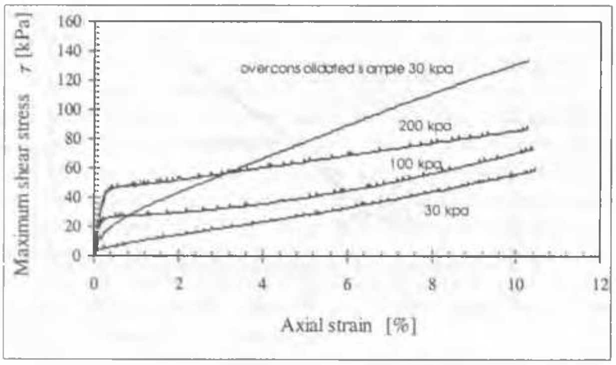

Figure 6. Shear strength of an artificially overconsolidated silt sample

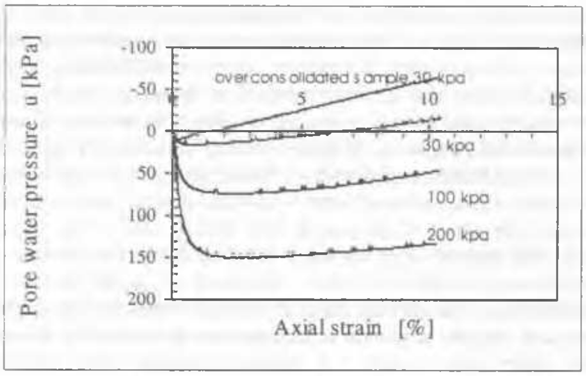

Figure 7. Pore water pressure versus axial strain for the overconsolidated sample

test results are shown in Figure 6 and 7 together with the other CCV tests results.

The overconsolidated sample has, as expected, higher undrained strength than that of the sample consolidated for 200 kPa confining pressure for a strain level exceeding 3%. Moreover, overconsolidation gives a more dilative behaviour than the samples run with confining pressure of 10 kPa. However, one should keep in mind that this man-made overconsolidation does not resemble the true overconsolidation for a natural sediment, since we are not able to develop the effects of aging and other chemical interaction between the soil grains.

7 MECHANISMS OF SILT BEHAVIOR

The structure and texture of the soil grains have a dominating influence on the mechanical behaviour of a soil. The fabric of the soil grains is a main factor for the behavior of sand, whereas electro-chemical bonding forces between the mineral grains control the characteristics of clay. For silts, both the above mentioned mechanisms may apply and effect the properties of silt.

It is well known that bonding forces between mineral grains are divided into two kinds, chemical and physical bonding forces, whereof the latter is considerably weaker. Physical bonding forces tend to dominate in silt, and silt is hence sensitive to changes in water content and easy to liquefy due to the weak bonding forces.

The pores in a sand material are large with a resulting high permeability, usually implying that drained conditions prevail during loading in situ. In contradiction, the system of pore channels in a clay is very small, the drainage properties is poor and undrained loading conditions usually apply in situ. For silt, the pore channels are large enough for water to move relatively freely, but small enough to make capillary effects obvious. The permeability coefficient is hence relatively small compared to that of sand, so the loading conditions are usually undrained or partially drained in the short - term case.

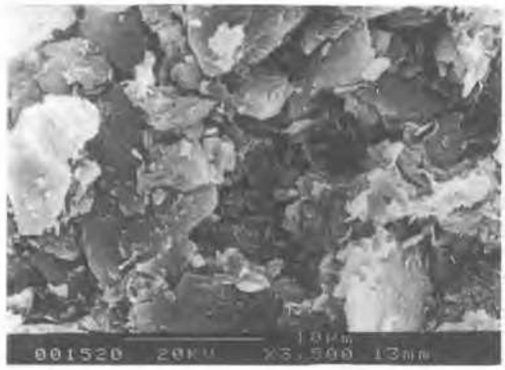

Figure 8. Microscopic photos on silt under the seafloor (Yang, 1995)

Some researchers have tried to study the mechanism and structure of silt materials using microscopes and advanced scanning techniques (e.g. Yang, 1995; Delage et al, 1996).

In such studies, silt particles are seen to be partly in direct contact with each other and partly surrounded by clay particles, see Figure 8. In some cases, clay particles may interconnect silt particles like a bridge. Such a structure is probably metastable, since it may be compressed during consolidation and shearing, and in some cases even result in a collapse of the soil structure.

Yu (1993) proposed a conceptual mode for sheared silt, see Figure 9. During the initial period of shearing, it is proposed that clay minerals between the sand and silt particles tend to be compressed, especially in the direction of the major principal stress. Some particles may also move into positions yielding a lower stress. Thus, the silt sample tends to contract at small strain levels in an undrained test, yielding an increase in pore pressures. At larger strains, however, the silt sample tends to dilate. In this situation there exist shorter distances between the sand and silt particles, and grains riding over interlocking particles may occur. On the other hand, the development of this interlocking effect is more easily constrained because of the existence of clay and the smaller size of silt particles than what is the case for a clean sand. This makes the behaviour of silt more dependent on the confining pressure.

Poul et.al. (1997) proposed a schematic diagram of silty sand in order to explain phenomena of static liquefaction. The material used in this study has a clay content of about 5%, a sand content of about 48%. In the sand fraction, fine sand is the dominant particle size with about 47%, and the material may be described as a sandy silt. The soil structure is compressed during the initial stage of shearing, and contractive behaviour could be observed from the undrained tests. When the strain level increases, the soil begins to dilate as expected.

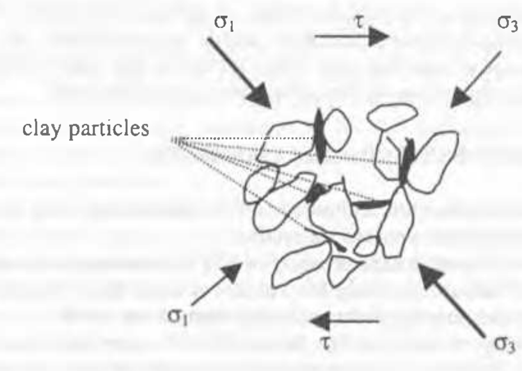

Figure 9. Conceptual mode for shearing of silt (Yu, 1993)

8 BEHAVIOR OF ISVA SILT UNDER CYCLIC LOADING

As commented on previously, silt is a material that easily loses its stability as a foundation material under given circumstances. A particular problem gaining much interest recently is the liquefaction potential for the foundations soils on the seabottom.

From an experimental model study, where the sinking and floatation of a pipeline in a silt bed was investigated (Sumer, 1999), the pipeline sank into the bed when this was exposed to progressive waves. The reason of this phenomena is the accumulation of pore water pressure in the silt bed, with the pore pressures eventually exceed the overburden pressure.

There has been collected a lot of experience on liquefaction of silty soils from various research programs, like for example the numerous investigations made on the seabottom of the enormous Yellow river subaqueous delta in China. However, few laboratory test programs on silty materials have been conducted, including advanced measurements such as cyclic triaxial tests.

In the study reported herein, cyclic triaxial tests were run on ISVA silt, a material that has been used extensively in laboratory model tests at the Danish Technical University in Copenhagen (Sumer, 1999). The cyclic test parameters were selected based on a 50 year return storm in the Bohai area:

- wave period: T = 8.6 s
- maximum wave amplitude: P = 25 kPa corresponding to a water depth of 8 m
- wave height 4.9 m from linear wave theory
- confining cell pressure: $\sigma_3 = 30$ kPa.

First, one cyclic triaxial test was conducted on a loose silt sample with porosity of 44.8 %. The cyclic load amplitude was about 26 kPa. This sample liquefied completely before the number of cycles reached 100. The pore pressure developed very fast and reached a plateau value between 20 and 30 cycles. After that, the pore pressure accumulated slowly for a large number of cycles, see Figure 10. Finally the sample liquefied at a total strain of more than 13 %.

For in situ conditions, it may take some time for waves to develop and increase, such as generation of waves during a storm period. The second cyclic test on silt was conducted according to the specifications Table 2, with test results as shown in Figure 11.

From the test results, pore pressures developed at a very low rate from the very beginning of the test at a cyclic load amplitude of 5 kPa. The accumulation rate increased after some 300 loading cycles. At the same time, there was no change in the strain level. After increase of the amplitude to 10 kPa, the pore pressure increased much faster, and there was some accompanying increase in the strain. From Figure 11 it is obvious that the amplitude of cyclic loading has great influence on the response of silt, both on the pore pressure and the deformation.
The stress path of this test is shown in Figure 12.

From the experimental study by Sumer et al (1999), the pattern of pore pressure build up in the silt bed is in good agreement with the results in Figure 11.

9 MAIN CONCLUSIONS

To summarize, here are some of the major observations in this test program:

- Silt may have dual characteristics at increasing strains, initially being contractive, then turning into a dilative behaviour at larger strains.
- The level of confining stress; consolidation state and porosity are the main influence factors on the behaviour of silt.
- The pore pressure usually develops very fast from the beginning of cyclic loading. The amplitude of the pore pressure increased gradually and showed an almost constant value when the sample was close to failure.

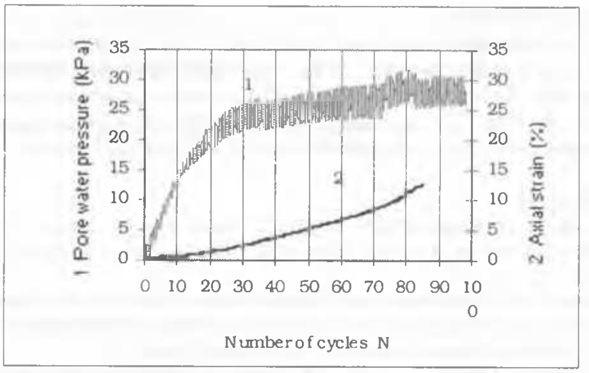

Figure 10*. Pore pressure and deformation during cyclic loading of silt $\Delta\sigma = 26$ kPa, $\sigma'_3 = 30$ kPa
*Strain after 90 cycles was not measured

Table 2. Cyclic triaxial test on silt (wave period 8.6 s, porosity 45.8%)

Step	Amplitude (kPa)	Loading time (min)
Step 1	5	60
Step 2	10	30
Step 3	15	30
Step 4	20	until failure

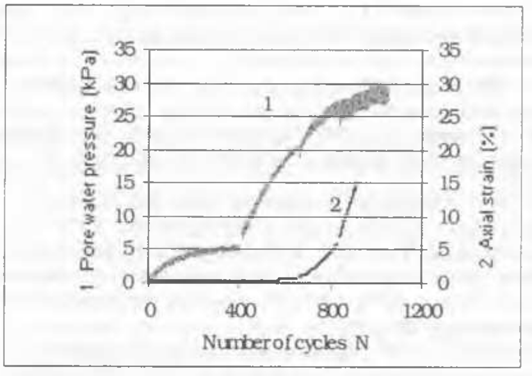

Figure 11*. Pore water pressure and deformation accumulated on silt at different amplitudes of cyclic loading, $\sigma_3 = 30$ kPa.
*Deformation after 850 cycles was not measured

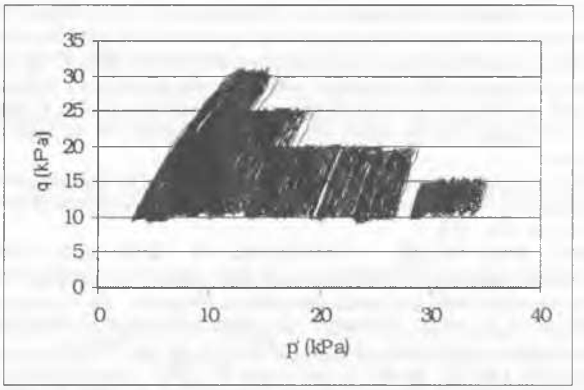

Figure 12. Stress path from cyclic triaxial test on ISVA silt.

- The average pore pressure increased quickly during the initial cycles, then increased slowly until liquefaction occurred at large strains.
- The pore pressure increased slowly at a small amplitude of cyclic loading, but increased fast at larger amplitudes.

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