Undrained behavior of sand under low cell pressure

Le comportement du sable en non-drainé sous basse pression

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ABSTRACT: Undrained behaviour of sand under low cell pressure was studied in static and cyclic triaxial tests. It was found that very loose sand liquefies under static loading, with the relative density being a key parameter for the undrained behaviour of sand. In the cyclic triaxial tests, pore water pressures built up during the cyclic loading and exceeded the confining cell pressure. This was accompanied by a large sudden increase in axial deformation. The necessary number of cycles to obtain liquefaction was related to the confining cell pressure, the amplitude of cyclic loading and the relative density of sand. In addition, patterns of pore water pressure response are different for sand samples with different relative densities. The test results are very useful for expounding scour mechanism around coastal structures since they relate to the low stress behaviour of the sand.

RÉSUMÉ: Le comportement en non drainé du sable sous basse pression interstitielle a été étudié par des essays triaxiaux statiques et cycliques. On a constaté que le sable trés lâche se liquefie sous un chargement statique; la densité relative étant un paramètre dé dans le compartement non drainé du sable. Dans l'essai triaxial cyclique, la pression interstitielle augmente pendant le chargement cyclique et dépasse la pression de confinement de la cellule. Ce compartement était accompagnié d'une subite augmentation de la deformation asciale.Le nombre nécessaire de cycles pour obtenir la liquefaction était relié à la pression de confinement de la cellule, à l'amplitude de la charge cyclique et à la densité relative du sable. De plus, les schémas de la réponse de la pression interstitielle sont différents pour les échantillons de sable seuvant leurs densités relatives.Les resultats de cet essai sont trés utiles pour expliquer le mecanisme de l'érosion autour des structures côtieres car ils sont reliés au comportement du sable sous faibles contraintes.

1 INTRODUCTION

Loose sand is a very common material throughout the world. In particular, there are numerous coastal and offshore structures resting on a sandy seabed, with many engineering problems due to the sand behaviour. Several instability phenomena due to decrease of sand strength have been reported in the literature. Some of them triggered structural failure due to loss of bearing capacity, some of them led to scour around the structure, eventually resulting in decrease of shear strength or temporary liquefaction. Thus, it is very necessary to study the behaviour of sand in a coastal environment where the confining stresses generally are low. Research in this field has not, however, received much attention.

There exist two kinds of typical sand behaviour. One is based on the test results on clean sand (Lee 1965), the other is based on results from tests on silty sands (Yamamuro et.al. 1998). In general, it is usually indicated that clean sands have a more dilative behaviour at low stress levels. This implies that clean sand is more stable at low stress levels compared to the behaviour at high stresses. This is usually not the case for silty sand, which is susceptible to static liquefaction under low stress level, completely loosing its strength. However, much research work is needed to study sand behaviour at low confining pressure in a systematic way.

2 INDEX PROPERTIES OF TESTED MATERIAL

In this study, a Norwegian Hokksund model sand was used as the test material. This material is a uniform, medium sand with sharp edged, cubical grains, which contains quartz (35%), Na-feldspar (25%), K-feldspar (20%), Mica (10%), amphibole (5%) and other minerals (5%). The most important index parameters may be summarized as follows:

- density of solid particles: ρ_s=2.71g/cm^3
- maximum porosity: n_{max}=48.7%
- minimum porosity: n_{min}=36.4%
- uniformity coefficient: C_u =2.04.

The grain size distribution curve is shown in Figure 1.

This sand material can hence be characterized as a clean sand without particles in the fine silt fraction.

3 SAMPLE PREPARATION METHODS

Many different preparation methods have been developed for preparation of artificial samples of sandy materials. The most used methods include wet tamping, dry deposition and water sedimentation of the grains. Each method may however have advantages and disadvantages. In this study, a dry deposition method through a funnel was used to prepare loose sand samples, whereas a dry sedimentation method using a special Danish procedure was used to prepare very dense samples (D_r = 100%) (Thøgersen and Kjeldsen, 1996). For the purpose of this study,

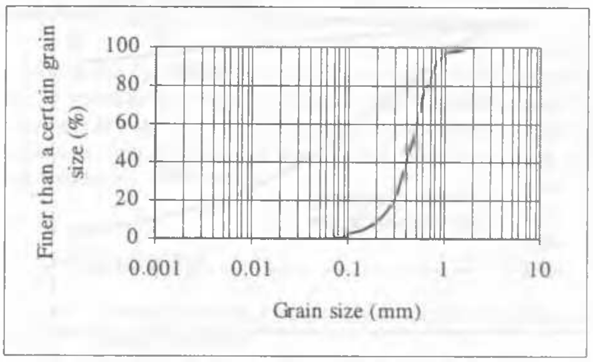

Figure 1. Grain size distribution curve of Hokksund sand

these methods have proven ideal for obtaining samples with repeatable properties.

It has been indicated by some researchers (Ishihara,1993; Been, 1991) that a wet tamping method may produce a more compressible sand sample, also enabling observations of very loose samples. Hence, tests with this preparation method were also carried out to study behaviour of loose samples. In fact, the term ''wet tamping'' is not a very descriptive name for the method, since very small energy was used during the procedure. A description such as ''moist layering preparation method'' is probably a better one.

The procedure may be described as follows:

- First, a certain amount of dried sand was mixed with distilled water at a water content of 5%
- Then the moisturized sand was left overnight. The whole weight of sand was divided into 10 parts with equal weight.
- The sand sample is prepared layer by layer in altogether ten layers, using the moist layering method
- The whole sample should be uniform during the process to prepare it.

4 STATIC UNDRAINED BEHAVIOUR OF SAND

Numerous consolidated undrained triaxial tests (CIU) were conducted in the laboratory test programme. Backpressures between 400 and 600 kPa were applied in all samples, with some of the samples also saturated by carbon dioxide (CO_2) before water saturation. All the test samples obtained a satisfactory high degree of saturation. All test results have been corrected for membrane effects, the effects being negligible for tests at high confining pressures. Some of the important test results are visualized in Figure 2 to 4.

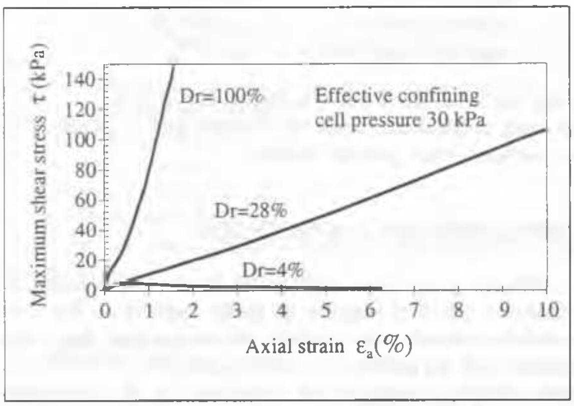

Figure 2. Typical stress - strain curve of sand sample

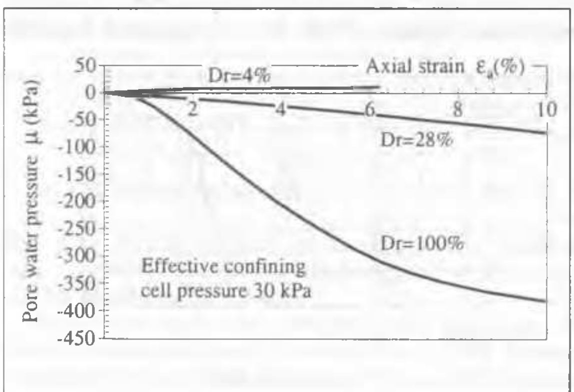

Figure 3. Pore water pressure developed during undrained triaxial test

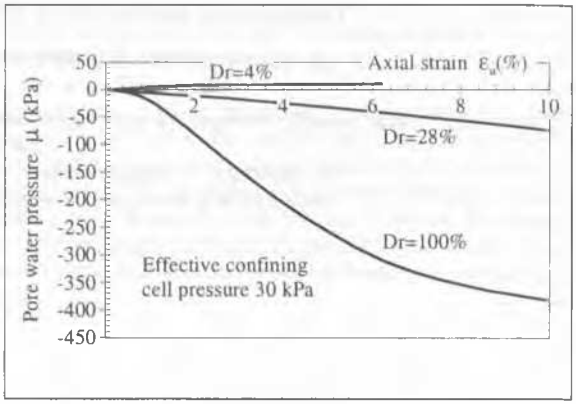

Figure 4. Stress path of sand during an undrained triaxial test

From the test results, we can clearly observe that the very loose sand samples show static liquefaction, with the shear stress becoming zero. In contradiction, the shear stresses of loose and dense samples approach higher values, and no instability phenomena are taking place. This may show that it is possible for a clean sand with very high porosity to completely loose its stability and develop static liquefaction at low stress levels.

5 CYCLIC UNDRAINED BEHAVIOR OF SAND

In this part of the study, one way cyclic loading was applied to sample in an undrained condition. Parameters selected for the cyclic triaxial tests on sand are listed below:

- wave period T=12 s
- wave amplitude P = 20 kPa (40 kPa), corresponding to water depth 5.0 m (10 m)
- wave height 4.0 m from linear wave theory
- confining cell pressure σ'_3= 30 kPa and σ'_3= 50 kPa
- porosity of sand
  D_r = 4% (prepared by moist layering method, very loose);
  D_r = 21% (prepared by dry sedimentation method, loose).

5.1 *Very loose sand*

Test results on very loose sand are shown in Figure 5 to Figure 8. They show that cumulative pore pressure developed from the start of cyclic loading. The pore pressure during one cycle is positive under the wave crest and negative under the wave trough. After cyclic loading was applied for about 160 cycles, the sand sample liquefied with pore water pressures exceeding 30 kPa (Figure 5). The deformation during this test was also accumulated and reached a failure value at the liquefaction state (Figure 6). If such conditions are developing at the sea bottom, it will of course lead to serious problem for the present structures. The soil will liquefy with resulting high pore water pressure and large deformation. Even a pre-liquefaction phase is dangerous since scour will take place around the structures due to accumulation of pore water pressures and resulting strength decrease.

The effect of increasing cell pressure on liquefaction susceptibility is also apparent. For samples consolidated at 50 kPa confining pressure, the number of cycles for the sand sample to liquefy is more than 300, whereas a number of about 160 cycles was needed for the sample at confining pressure 30 kPa (Figure 7 to 8).

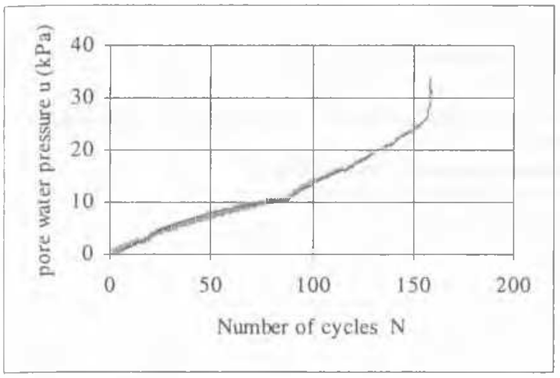

Figure 5. Pore water pressure accumulated until liquefaction occurred $\Delta\sigma$=20 kPa, σ'_3= 30kPa

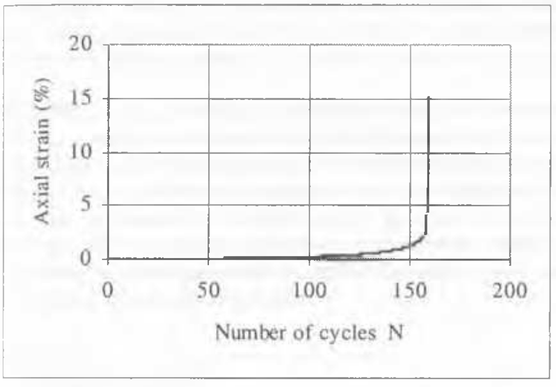

Figure 6. Axial strain accumulated until liquefaction occurred $\Delta\sigma$=20 kPa, σ'_3= 30kPa

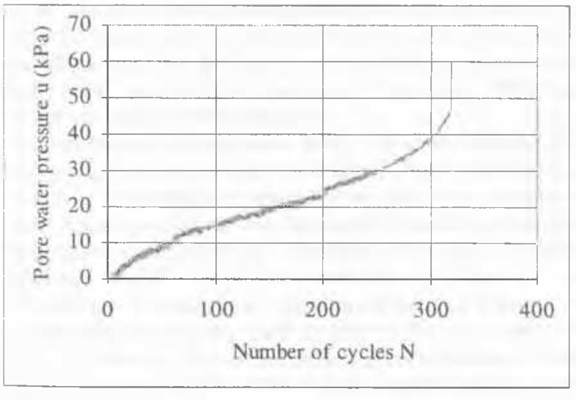

Figure 7. Pore water pressure accumulated until liquefaction occurred $\Delta\sigma$=20 kPa, σ'_3= 50kPa

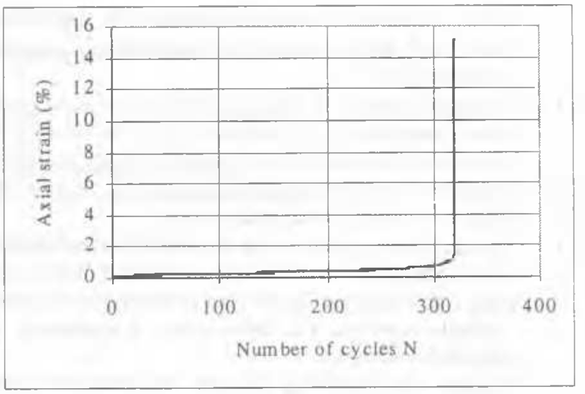

Figure 8. Axial strain accumulated until liquefaction occurred $\Delta\sigma$=20 kPa, σ'_3= 50kPa

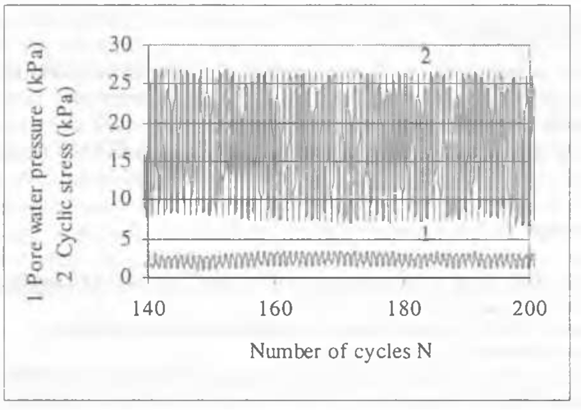

Figure 9. Pore water pressure developed from 140 cycles to 200 cycles $\Delta\sigma$=20 kPa, σ'_3= 30kPa

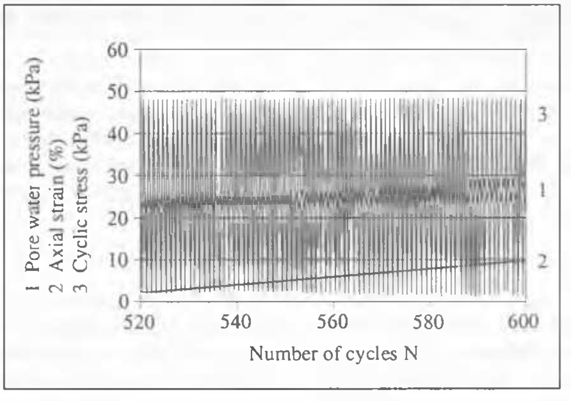

Figure 10. Pore water pressure developed after stress amplitude was changed $\Delta\sigma$=40 kPa, σ'_3= 30kPa

5.2 *Loose sand*

The effect of cyclic stress amplitude is indicated in Figures 9 and 10. The pore water pressure response to cyclic loading (P = 20 kPa) is marginal, only about 2 kPa after 140 cycles, and keeps almost constant over a long cycling period (Figure 9). Later on in the test, the wave amplitude was changed from 20 kPa to 40 kPa, with a sudden pore water pressure increase during the first cycles and with a continued accumulation thereafter (Figure 10). Deformation also increased simultaneously. As one should expect, the amplitude of cyclic load has considerable influence on the generated pore water pressure.

From the figures above, we can see that the deformation increase considerably when the sand liquefied, and the sand looses its strength very quickly. In a coastal environment, such kind of behaviour will decrease the strength and accelerate scour around the structure.

6 CONCLUSIONS

- The porosity plays a dominant role in the behaviour of a sand sediment.
- Dense sand has a dilative behaviour at large strain levels, and the material approach large shear stresses.

- Loose sand has a contractive behaviour at large strain levels, and the corresponding shear stresses may be extremely low.
- When the porosity is very high, even clean sand could show temporary static liquefaction due to increase of pore water pressure over a short period in undrained conditions. Very loose sand is susceptible to lose stability even at very small strain levels.
- The amplitude of pore water pressure decreased gradually during cyclic load for very loose sand, but the average value increased faster and faster until the sample suddenly liquefied. This behaviour is accompanied by large deformations.
- The less the confining pressure, the faster the sand loses its stability.
- The larger the amplitude of cyclic loading, the easier the sand liquefies.

Acknowledgements

The experimental work was conducted at the Department of Geotechnical Engineering, NTNU. The authors appreciate very much the help and suggestions from the laboratory staff.
Parts of this work were supported by the EU SCARCOST project.

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