Behavior of marine silty sand subjected to long term cyclic loading

Comportement du sable limoneux marin soumis à une charge cyclique de longue durée

Safdar M., Kim J.M.
Pusan National University, Busan, South Korea

ABSTRACT: The foundations for offshore wind turbines are demanding due to the dynamic nature of the offshore loading. A greater understanding of the behavior of wind turbine foundation soil, will certainly lead to the stable construction of foundations which in turn, will make offshore wind farms a more feasible part of the solution to the global energy problem. This paper presents the results of cyclic direct simple shear test (CDSS) to explain the long term cyclic behavior of marine silty sand. Cyclic behavior of marine sand are based on the number of loading cycles, cyclic shear strain amplitude, relative density, and cyclic stress ratio. These results are modeled and can be applied to design offshore wind turbine foundations.

RÉSUMÉ : Les fondations pour les éoliennes offshore sont principalement exigeante en raison de la nature dynamique du chargement offshore. Une meilleure compréhension du comportement de l'éolienne des sols de fondation, va certainement conduire à la construction des fondations stables qui à leur tour, feront de parcs éoliens en mer un rôle plus possible de la solution au problème mondial de l'énergie. Ce document présente les résultats d'essai de cisaillement cyclique directe simple (CDSS) pour expliquer le comportement cyclique à long terme de sable limoneux marin. Comportement cyclique de sable marin sont basés sur le nombre de cycles de charge, cyclique d'amplitude de contrainte au cisaillement, la densité relative et du taux de contrainte cyclique. Ces résultats sont modélisés et peut être appliquée à la conception fondations d'éoliennes off-shore.

KEYWORDS: *Cyclic Loading, Offshore Wind Turbine, CDSS, Cyclic Stress Ratio*

1 INTRODUCTION

Understanding the behavior of offshore marine sand subjected to long term cyclic loading is very vital in solving several offshore geotechnical problems. Several researchers have studied behavior of clay and sand subjected to cyclic loading.

(Vucetic et al. 1988) studied the degradation of marine clays under cyclic loading. (D. Wijewickreme et al. 2005) studied the cyclic loading response of loose air-pluviated Fraser river sand. (K.H. Andersen 2009) investigated in detail, the bearing capacity of the soil under cyclic loading, and stated that the cyclic shear strength and the failure mode under cyclic loading depend on the stress path and the combination of average and cyclic shear stresses. Safdar et al., 2013, studied the cyclic behavior of marine silty sand subjected to symmetrical cyclic loading. Different approaches have been made as an attempt to include cyclic loading in the design procedure of offshore wind turbine foundation (Soren et al. 2012).

1.1 *Stress controlled CDSS test*

Constant volume direct simple shear (DSS) test is a reliable method for measuring undrained shear strength of undisturbed or compacted soil samples. The DSS test is most similar to the CU triaxial test in that samples are consolidated prior to shearing. The simple shear is the test condition that only normal and shear stress acting on top face of a specimen is defined, whereas the displacement constraints exist for the other boundaries: The bottom face of specimen is theoretically fixed, and the radial strain on specimen is zero.

The CDSS test procedure is based on that of a constant-volume direct simple shear testing of soils, which has been studied extensively for half a century and is described in the standard ASTM D6528-07. The sample is consolidated under a normal load within a wire-reinforced membrane (in this study) or a stack of thin rings that provide lateral confinement.

Once consolidation is complete, a horizontal shear force is applied to one end of the sample. The sample height is continuously maintained during shear to ensure constant volume. Rather than measuring pore pressures, which would require complete saturation of the sample, the pore pressure response is inferred from the change in vertical stress which is monitored throughout the test (Baxter et al 2010). In this way changes in applied vertical stress ($\Delta\sigma_v$), which are required to keep the sample height constant, are assumed to be equal to the excess pore water pressure (Δu) that would develop if the test were truly undrained with pore pressure measurements (Finn, 1985, Dyvik et al. 1987).

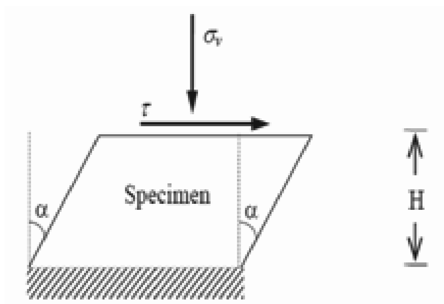

Figure 1 Simple Shear Condition, (Dyvik et al 1987)

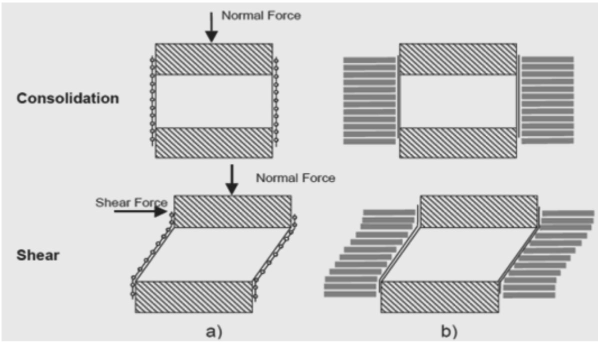

Figure 2 (a). Wire Reinforced Membrane (b). Stacked Rings (Baxter et al 2010)

The cyclic shear response of natural low-plastic Fraser River silt was investigated using constant-volume direct simple shear (DSS) testing (Wijewickreme 2010). Maria V. Sanin et al., (2011) studied the cyclic shear response of undisturbed and reconstituted Fraser River Silt. A soil can be subjected to many different stress conditions, being purely cyclic stress, static or average stress, or a combination of both. Andersen (2009) shows this clearly in a study on Drammen clays at the NGI. Drammen clays samples are tested in cyclic triaxial and cyclic simple shear conditions for different combinations of static and cyclic shear stresses. In this study cyclic simple shear tests have been performed with static or average shear stress, α = 0 or symmetrical cyclic loading.

1.2 *Sample Preparation*

Air Pluviation with dry compaction approach was developed to produce samples of the silty sand with consistent heights and initial relative densities. The equipment used consists of the shear box having bottom cap, two o-rings, wire-reinforced membrane, top cap, triaxial pressure panel, and compacting hammer. Sample diameter is 63.5mm and height is varied from 20 to 25 mm to maintain height to diameter ratio less than 0.4, in order to fulfill the ASTM D6528-07 criteria. In this study marine silty sand is obtained from the West coast of South Korea. Specific gravity of material tested is Gs =2.65. Marine silty sand has minimum voids ratio of 0.74 and maximum voids ratio of 1.18. Details of properties of soil tested are given in Table 1.

Table 1 Properties of marine silty sand.

Properties of Soil Tested	
Min. Voids Ratio	0.74
Max. Voids Ratio	1.18
Coefficient of Uniformity	1.8 mm
D_{10}	0.08 mm
D_{30}	0.09 mm
D_{60}	0.14
USCS	Silty Sand (SM)
Specific Gravity (Gs)	2.652

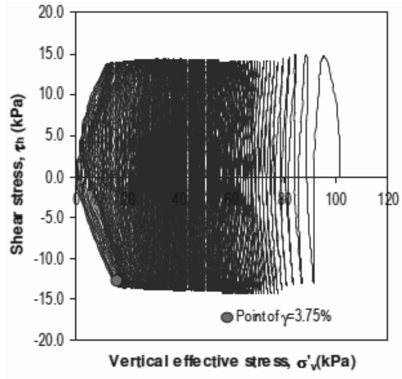

Figure 3 Stress-path responses of NC Fraser River silt under constant volume cyclic DSS loading (σ'$_v$ = 97 kPa; CSR = 0.20; α=0; OCR = 1.0) (Maria V. Sanin et al., 2011).

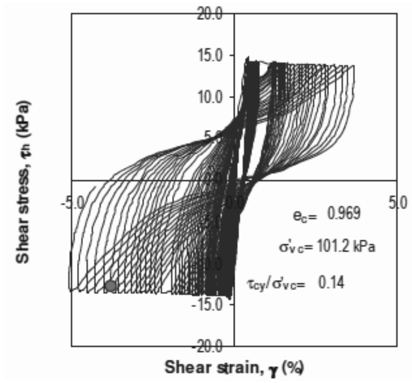

Figure 5 Constant volume cyclic DSS test on undisturbed Fraser River Delta silt. (σ'$_v$ = 100 kPa, CSR = 0.14) (Maria V. Sanin et al., 2011).

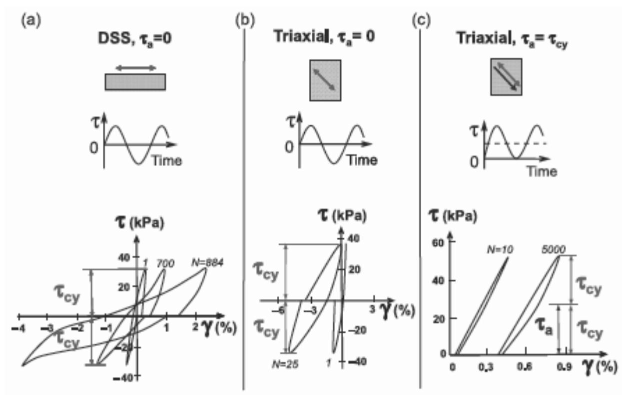

Figure 5 Stress-strain behavior under different loading conditions (Andersen, 2009)

1.3 *Testing Program*

The laboratory testing program for this study was designed to analyze the behavior of marine silty sand when subjected to cyclic loads for different combinations of parameters such as cyclic stress ratio, no. of loading cycles and relative density.

For marine silty sand, the tests were performed at a frequency of 0.1 Hz. Effect of Relative Density (Dr %) for 65, and 70 percent is studied for various CSR and no. of loading cycles. Marine silty sand has minimum voids ratio of 0.74 and maximum voids ratio of 1.18. Specific gravity of Gs=2.65.

To produce in-situ (K_0) stress conditions, a vertical consolidation stress must be applied to the sample prior to shearing. Applied vertical stresses simulate the loads from overburden material located over the soil sample. For marine silty sand, a normal consolidation stress of 100 KPa was applied in one step for all the specimens.

1.4 *Cyclic Direct Simple Shear test results*

Several researchers have used different shear strain failure criteria such as 3%, 4%, 5% and 7.5%. A shear strain failure condition was used for tests performed on marine silty sand and the failure criterion was established as 4% double amplitude shear strain. The results of a test are shown in Figure 6, 7 and 8.Figure 8 shows the applied cyclic shear stress of +/- 12 kPa (CSR = 0.12). Figure 6 shows the development of shear strain throughout the test, which reaches 4% double amplitude shear strain at nearly 205 cycles.

8 CDSS tests were conducted, 4 tests at voids ratio of 0.898 (Dr 65%) and CSR range of 0.10, 0.12, 0.14, and 0.16. 4 tests at voids ratio of 0.847 (Dr 70% and CSR range of 0.10, 0.12, 0.14, and 0.20. All the tests were conducted at nominal initial effective confining stress of 100 kPa to provide a basis for comparison between tests. In case of 70% relative density, Figure 6 shows the degradation curve and development of shear strain with increasing number of cycles. In a general sense, marine silty sand specimens seem to exhibit gradual increase in shear strain and degradation of shear stiffness with increasing number of load cycles. Typical stress paths and stress-strain curves of tests conducted on marine silty sand specimens are presented in Figures 7 and 8 respectively.

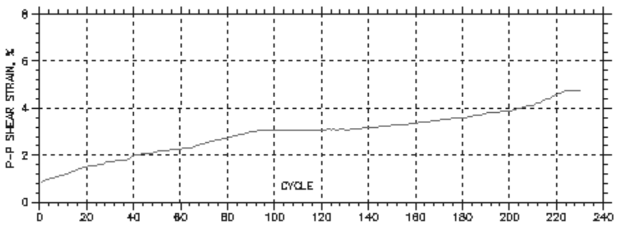

Figure 6 Peak-Peak Shear Strain vs No. of Loading cycles for (σ'_v = 100 kPa, CSR=0.12 and Dr (%) = 70).

Figure 6 shows that samples having relative density of 70% reached 2% cyclic double amplitide cyclic shear strain after 42 cycles and 205 to reach failure.

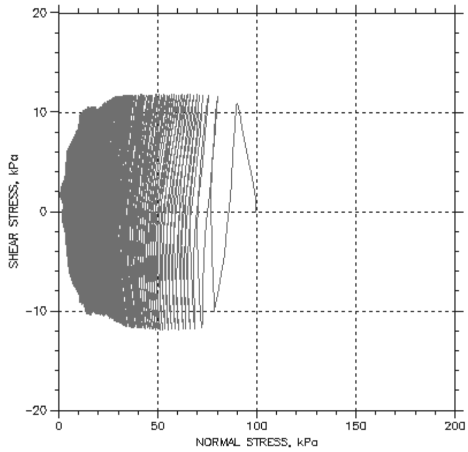

Figure 7 Stress Path During constant volume cyclic DSS loading of silty sand for (σ'_v = 100 kPa, CSR=0.12 and Dr (%) = 70).

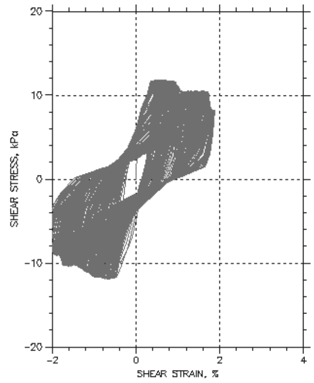

Figure 8 Stress-strain response of marine silty sand under constant volume cyclic DSS loading (σ'_v = 100 kPa; Dr (%) = 70, CSR = 0.12; α= 0.0; OCR = 1.0).

In case of 65% relative density, Figure 9 shows the degradation curve and development of shear strain with increasing number of cycles. Typical stress paths and stress-strain curves of tests conducted with 65% relative density on marine silty sand specimens are presented in Figures 10 and 11 respectively.

It was observed that specimens having higher relative densities require higher no. of loading cycles to reach 4% double amplitude cyclic shear strain and specimens having lower relative density reach to failure in smaller no. of loading cycles. In case of higher cyclic stress ratio (CSR) the soil samples reached the failure criterion in few no. of loading cycles.

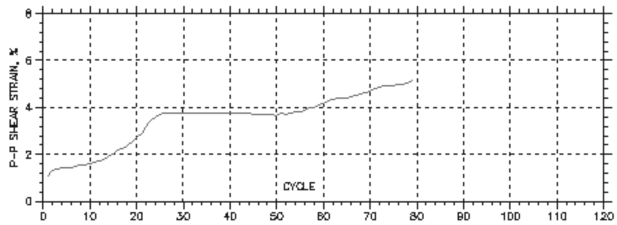

Figure 9 Peak-Peak Shear Strain vs No. of Loading cycles for (σ'_v = 100 kPa; Dr (%) = 65, CSR = 0.12; α= 0.0; OCR = 1.0).

Figure 9 shows that samples having relative density of 65% reached 2% cyclic double amplitide cyclic shear strain after 15 cycles and 57cycles to reach failure.

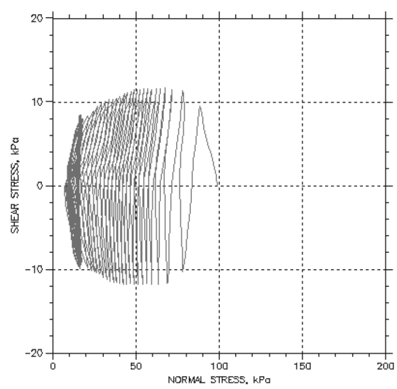

Figure 10 Stress Path During constant volume cyclic DSS loading of silty sand for (σ'_v = 100 kPa; Dr (%) = 65, CSR = 0.12; α= 0.0; OCR = 1.0).

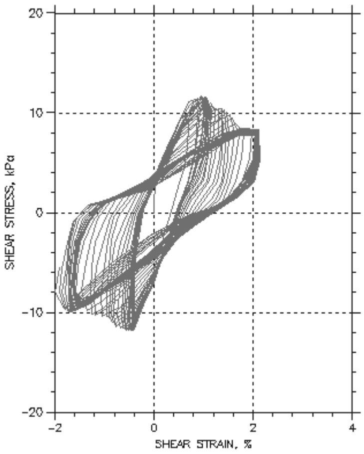

Figure 11 Stress-strain response of marine silty sand under constant volume cyclic DSS loading (σ'_v = 100 kPa; Dr (%)= 65, CSR = 0.12; α= 0.0; OCR = 1.0).

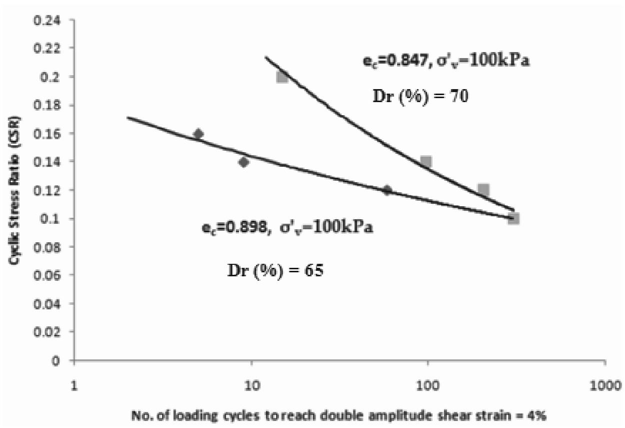

Figure 12 CSR versus No. of Loading cycles to reach double amplitude shear strain of 4% for marine silty sand

Figure 12 shows the number of loading cycles versus cyclic stress ratio that reach shear strain of 4%. As expected, samples having higher value of cyclic stress ratio and/or low relative density fail at a small number of loading cycles. It is found in this particular study that the number of loading cycles required to reach the threshold strain is not much different for two relarive densities after 300 loading cycles. The trends are little different from the previous study reported (Fig. 13) in which the curves are almost parallel even in high number of cycles.

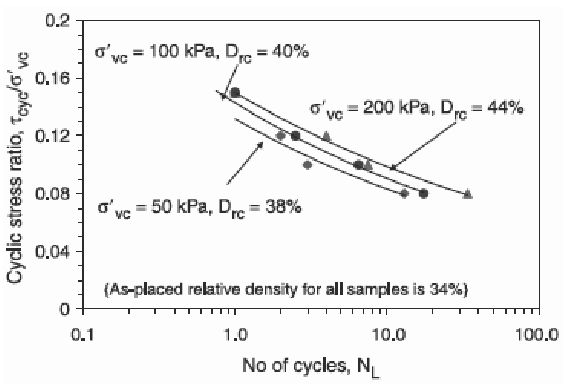

Figure 13 Effect of stress densification on cyclic resistance of loose air-pluviated sand (Wijewickreme et al., 2005)

Samples having 70% relative density and subjected to CSR of 0.12 reached cyclic double amplitude of 4% shear strain at nearly 205 cycles. In case of samples having 65% relative density and subjected to CSR of 0.12 reached cyclic double amplitude of 4% at nearly 57 cycles.

2 SUMMARY AND CONCLUSIONS

The constant volume cyclic shear response of marine silty sand was examined using data from CDSS tests.
The intent was to compare the shear response of the silty sand specimens under different relative densities.
samples having higher value of cyclic stress ratio and/or low relative density fail at a small number of loading cycles. It is found in this particular study that the number of loading cycles required to reach the threshold strain is not much different for two relarive densities after 300 loading cycles. The trends are little different from the previous study reported in which the curves are almost parallel even in high number of cycles.

3 ACKNOWLEDGEMENT

This research is supported by the Ministry of Land, Transport and Maritime Affairs, Korea 2010 research grant (2010 Construction Technology Innovation Program, 10-CTIP-E04).

4 REFERENCES

Andersen K.H 2009. Bearing capacity under cyclic loading- offshore, along the coast, and on land. The 21st Bjerrum Lecture presented in Oslo, 23November 2007". *NRC Research Press* Web site (www.cgj.nrc.ca)

Baxter C.D.P, Bradshaw A.S., Ochoa-Lavergne M. and Hankour R. 2010. DSS Test Results using Wire-Reinforced Membranes and Stacked Rings. *GeoFlorida 2010 ASCE*.

Boulanger R.W & Seed R.B. 1995 . Liquefaction of sands under Bidirectional monotonic and cyclic loading. *Journal of Geotechnical Engineering ASCE* Vol. 121, No. 12 pp. 870-878.

Bjerrum, L., and Landva, A. 1966. Direct simple-shear tests on a Norwegian quick clay. *Geotechnique* 16(1), 1-20.

Dyvik, R., Berre, T., Lacasse, S., and Raadim, B. 1987. Comparison of truly undrained and constant volume direct simple shear tests. *Geotechnique* 37(1), 3-10.

Idriss, I. M., and Boulanger, R. W. 2008. Soil liquefaction during Earthquakes. Monograph MNO-12, *Earthquake Engineering Research Institute, Oakland, CA*.

Maria V. Sanin, Wijewickreme D. 2011. Cyclic shear response of undisturbed and reconstituted Fraser River Silt. *Pan-Am CGS Geotechnical Conference.*

Safdar M., Kim, J.M. (2013). "Cyclic Behavior of Marine Silty Sand" *Electronic Journal of Geotechnical Engineering (EJGE)* Vol.18A, pp. 209-218.

Soren K. N., Amir Shajarati, K.W.Sorenson, L.B. Ibsen 2012. Behaviour of Dense Frederikshavn sand during cyclic Loading. *DCE Technical Memorandum No. 15*

Vucetic M. & Dobry R. 1988. Degradation of marine clays under cyclic loading. *Journal of Geotechnical Engineering ASCE* Vol. 114, No. 2 pp. 133-149.

Wijewickreme D. 2010. Cyclic shear response of low plastic Fraser River silt. *Proceedings of the 9th U.S. National and 10th Canadian conference on Earthquake Engineering*

Wijewickreme D., Sanin M.V. and Greenaway G.R. (2005) Cyclic shear response of fine-grained mine tailings. *Canadian Geotechnical Journal* Vol. 42 pp. 1408-1421

Wijewickreme, D., Sriskandakumar, S., and Byrne, P. 2005. Cyclic loading response of loose air-pluviated Fraser River sand for validation of numerical models simulating centrifuge tests. *Canadian Geotechnical Journal* 42(2), 550-561.