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Monotonic and cyclic behaviour of gravelly sand

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ABSTRACT: Both monotonic drained and cyclic undrained tests are performed in large triaxial aparatus. Sand contents of 100%, 80%, 65% and 50% are selected for the tested sand-gravel mixtures. The purpose of the study is to evaluate effect of gravel contents on behaviour of sand-gravel mixtures. Discussion on important parameters for evaluating the static and cyclic strength of gravelly sands is given. This paper presents an interpretation of the monotonic and cyclic large size triaxial tests on clean sand and sand-gravel mixtures, including contour diagrams of cyclic strength and strain development. The test results indicated that static compression strength is changing with variations of gravel contents for sand-gravel mixtures. However there is no clear trend on cyclic strength. The results are expected to be of significant value for offshore windfarm foundation design..

Keywords: Sand-gravel mixtures, monotonic and cyclic behaviour, large triaxial cell, contour diagrams

1 INTRODUCTION

Cyclic strength and deformation characteristics of gravelly sands are important for the foundation design of offshore wind turbines and other offshore structures. Proper foundation design requires an understanding of both monotonic and cyclic behaviour of soils around the foundation, including information on cyclic shear strength, pore pressure and deformation characteristics. Contour diagrams have been used intensively to present cyclic parameters required for foundation design. The Norwegian Geotechnical Institute (NGI) has used the contour diagram framework for practical foundation design in both clay, silt and sand for many years and a database has been developed on various soils (e.g., Andersen, 2004, 2015; Andersen et al., 1980, 1988a, 1988b; Blaker and Andersen, 2019; Yang, et al., 2023). The data base reflects the effect of the fines content in the behavior of silt and sands. Measured laboratory data is utilized to draw the contour diagrams and cyclic soil parameters are provided from all relevant cyclic contour diagrams. In addition, the cyclic parameters are basis for development of constitutive cyclic soil models, and they can be used to check constitutive soil models for different stress conditions.

Gravelly sands are common in shallow waters at offshore wind farm sites all over the world, however there are very few available cyclic strength and deformation data on these soils. One reason is due to gravel size since standard soil element tests can not be performed on sands with gravel larger than about 4 mm. This paper presents an interpretation of the monotonic and cyclic triaxial tests on the reconstituted sand and sand-gravel mixtures, including contour diagrams of cyclic strength and strain development. The purpose of this study is to discuss monotonic and cyclic behaviour of gravelly sands and try to improve the understanding of behaviour of sand-gravel mixtures. The result adds new data to contour diagrams for sand- gravel mixtures.

2 MATERAILS USED IN THE EXPERIMENTAL WORK

Clean sand used in this study is rounded to subrounded, well spherical, containing 98% quartz. Clean gravel is subrounded to rounded, well spherical, containing 90% dolomite and 5-10%

of quartz. Clean sand and clean gravel are mixed to get gravel-sand mixtures with various sand content for this study. Grain size distributions for the tested materials are shown in Figure 1. Table 1 shows a summary of relevant soil parameters for the tested materials. In Figure 1, one additional grain size distribution test was performed after one triaxial test for sand-gravel mixtures with 50% sand and the purpose is to check possible grain crushing effect. The results did not indicate any significant particle crushing after the test. All index tests were performed according to GBT20123 (2019).

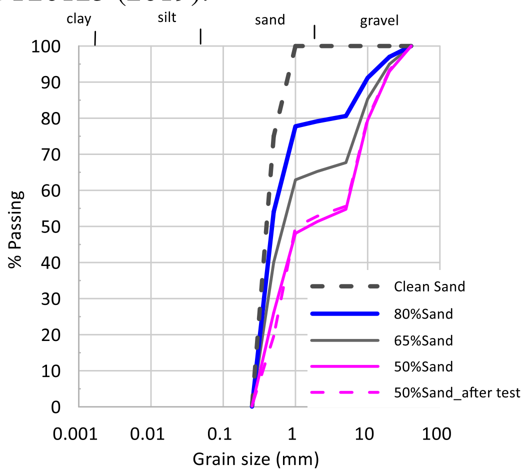


Figure 1 Grain size distribution curves for the tested sand-gravel mixtures

Table 1. Summary of relevant soil parameters for the tested materials

Name	γ_{max} (kN/m^3)	γ_{min} (kN/m^3)	w_c (%)	D_{rc} (%)
Clean Sand	16.17	13.43	27.5	73.7
80% Sand	17.93	15.68	19.8	75.8
65% Sand	19.11	17.05	16.1	74.9
50% Sand	20.48	17.93	15.6	69.2

γ_{max}: maximum dry unit weight, γ_{min}: minimum dry unit weight, w_c, average water content after consolidation, D_{rc}, average relative density after consolidation.

3 LABORATORY PROGRAM AND TESTING PROCEDURES

The laboratory program consisted of seven drained monotonic and thirteen cyclic large size triaxial tests. 5 cyclic tests were performed on clean sand, and three of five tests with $\Delta\tau_a$=0 and two of five tests with $\Delta\tau_a$>0, $\Delta\tau_a$ is applied by increasing vertical stresses. 3 cyclic tests on 80% Sand and 50% sand, respectively and 2 cyclic tests on 65% Sand. 2 monotonic tests were performed for clean sand, 80% Sand and 65% sand, respectively. Only one CADC test was carried out on 50% Sand.

All specimens were reconstituted by moist tamping method. Cyclic tests were performed with drained average shear stress for two of the tests on clean sand. The subsequent cyclic loading was performed undrained. All tests were consolidated to 200 kPa with k_0 = 0.45. The key results are summarized in Table 2.

Table 2. Summary of key result from monotonic tests

Name	**τ_f/σ'_{ref}, CADC**	**ϕc**	**τ_f/σ'_{ref}, CADE**	**ϕE**
Clean Sand	0.69	35.9	-0.20	44.5
80% Sand	0.88	39.4	-0.19	38.7
65% Sand	0.82	39.5	-0.20	43.5
50% Sand	0.64	36.5	-	-

3.1 Specimen preparation

There are several methods that can be used to prepare reconstituted specimens. Among them are moist tamping, air pluviation, water sedimentation and slurry deposition (Amini and Qi, 2000; Chien, et al., 2002, Yang, 2004, Sadrekarimi and Olson, 2012; Mahmoudi et al., 2019; among others).

The moist tamping method is selected for this study because uniform samples can be made (Chien, et al., 2002; Ladd, 1978; Vucetic and Dobry, 1988). In the experimental work, all specimens were prepared by moist temping at around 3% water content to target relative densities using under-compaction with five equal volume lifts, based on a slightly modified version of the method described by Ladd (1978). The Triaxial apparatus used in this study was the Tsinghua type described in Zheng, et al., 2011. A cylindrical specimen with a diameter of 30 cm and height of 62.5 cm was placed within a rubber membrane. All samples were prepared with an initial relative density of 60%.

3.2 Consolidation and pre-cycling procedures

The specimen was usually consolidated in two steps before shearing. For each step, a continuous rate of applying load is 1.4kPa/s. After consolidation the specimen was subjected to pre-cycling, which was applied drained to simulate in situ conditions both beneath and outside the foundation during the build-up period of the design storm or during small storms prior to the design storm. The pre-shearing was performed with 400 cycles using a cyclic shear stress of

4% of the vertical consolidation stress for all tests. The pre-shearing also ensures the contact and good seating between the sand-gravel mixtures and the end plates and rubber membrane. The consolidation and the pre-shearing were the same for monotonic and cyclic tests.

Static and cyclic shear strengths show non-linear correlation with consolidation stresses. The consolidation stress effect can be taken into account by normalizing by a reference stress (Andersen 2015), $\sigma'_{ref} = p_a(\sigma'_{vc}/p_a)^n$, where p_a is the atmospheric pressure (100 kPa) and n is an exponent, ranging from 0.9 to 0.1, depending on the shear strength. This normalization is used in this study for stresses and strengths to make the results more generally valid.

3.3 Monotonic and cyclic tests

The static shear strength was defined as the shear stress at 15% shear strain if no distinct peak occurred at a lower strain level.

The cyclic loading was applied as a stress controlled sinusoidal pulse with a load period of 10 seconds by an hydraulic servo loading system. The consolidation procedure for a cyclic test is the same as for a monotonic test. The cyclic tests are performed with both symmetric and non-symmetric cyclic shear stresses, i.e., with and without an average shear stress during cycling on clean sand. First, if any, the $\Delta\tau_a$ is applied under drained conditions for about one hour before cyclic testing. A two-way cyclic shear stress is then applied to the specimen around the τ_a (average) or shear stresses after consolidation. The cyclic phase continued up to 1500 cycles or to a cyclic or average shear strain of at least 15%, whichever occurs first.

4 MONOTONIC BEHAVIOUR OF TESTED MATERIALS

Figures 2 and 3 show test results from monotonic triaxial tests. The stress strain curves are shown in a blown-up scale in Figures 2b and 3b, since the shear strains below peak shear stress are relevant for calculating structure displacements and the soil stiffness in the dynamic analysis. It is useful to evaluate stress-strain behaviour at small strain levels.

Undrained shear strength in extension for all the tested samples is similar. However undrained shear strength in compression showed significant difference. Normalised undrained compression strength is increased from 100% sand to 80% and 65% sand samples, and the strength is decreased at 50% sand content sample. Drained peak frictional angle for clean sand and 65% sand samples from CADE are much higher than those from CADC tests which need to be studied further.

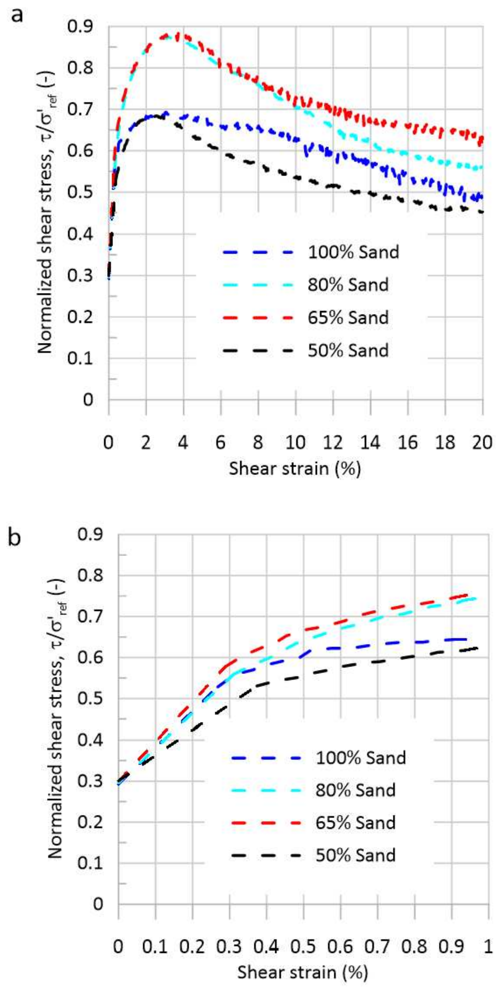
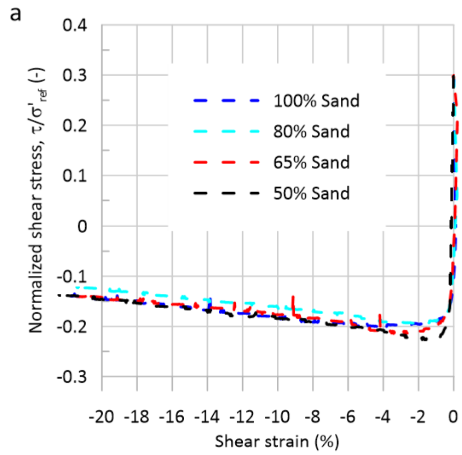


Figure 2 Normalized shear stress versus shear strain for drained CADC tests
a) Shear strain 0 to 20%, b) Shear strain 0 to 1%.



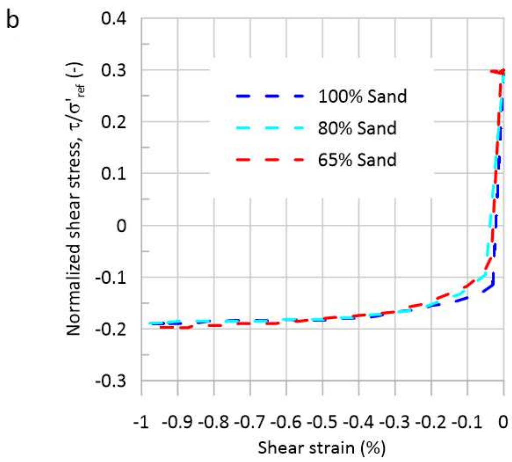


Figure 3 Normalized shear stress versus shear strain for drained CADE tests

a) Shear strain 0 to 20%, b) Shear strain 0 to 1%.

5 CYCLIC BEHAVIOUR OF TESTED MATERIALS

Table 3 summarized all cyclic test results. Average shear strains reached 15% for most of the tests, except one test, Clean Sand CAUcy4. $\Delta\tau_a$ is applied under drained conditions for about one hour before two-way cyclic loading for Clean Sand tests CAUcy4 and CAUcy5.

Table 3 Summary of the key result from cyclic tests

Name	τ_a/σ'_{ref}	τ_{cy}/σ'_{ref}	N_f	γ_a	γ_{cy}
Clean Sand-1	0.31	0.45	10	15.0	0.51
Clean Sand-2	0.29	0.42	20	15.0	1.7
Clean Sand-3	0.28	0.38	393	15.0	0.2
Clean Sand-4	0.01	0.20	23	11.0	15.0
Clean Sand-5	0.50	0.47	240	15.0	0.1
80% Sand-1	0.34	0.43	16	15.0	3.3
80% Sand-2	0.29	0.43	188	15.0	2.5
80% Sand-3	0.34	0.44	11	15.0	7.5
65% Sand-1	0.31	0.44	17	15.0	5.1
65% Sand-2	0.29	0.43	80	14.7	3.3
50% Sand-1	0.31	0.48	43	15.0	3.8
50% Sand-2	0.30	0.44	268	15.0	2.5
50% Sand-3	0.29	0.38	1094	14.9	1.2

τ_a/σ'_{ref}: Normalized average shear stress
τ_{cy}/σ'_{ref}: Normalized cyclic shear stress
N_f: Number of cycles at failure
γ_a: Average shear strain in percentage
γ_{cy}: Cyclic shear strain in percentage

A set of cyclic contours are drawn for clean sand, which are given in Figures 4a, 4b, 4c and 4d. One observation from Figure 4b is that failure contours combining all available monotonic and cyclic triaxial tests in large triaxial cell is not very different from what was developed on clean sand from soil element tests (Andersen, 2015). All other cyclic tests are also given in the failure contours in Figure 5. It seems there is no clear tendency regarding cyclic strength as we observed on static strength based on CADC tests. However, at an average shear stress ratio about 0.3, cyclic strength for 50% sand samples (black symbols in Figure 5) is the highest among all tested samples.

For some cyclic tests, the shear stress could not be kept constant when the strains approached 15%. This is considered when drawing cyclic contours. Because of the limited number of tests, cyclic contour diagrams are drawn based on engineering judgement and possible extrapolation of tested data. This methodology is normally applied to practical project work since only a few tests can be performed for engineering projects.

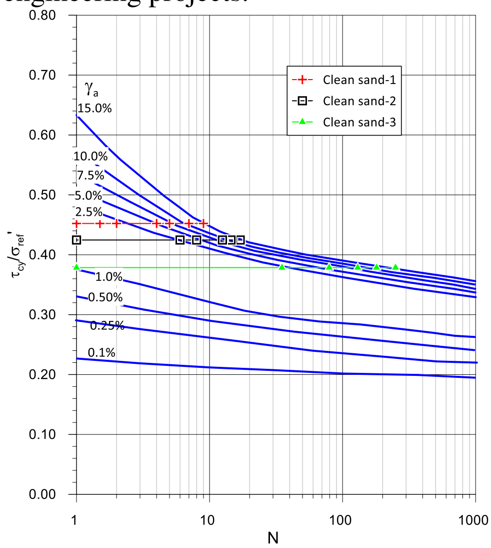


Figure 4a Normalized shear stress versus number of cycles on clean sand, average relative density 62%.

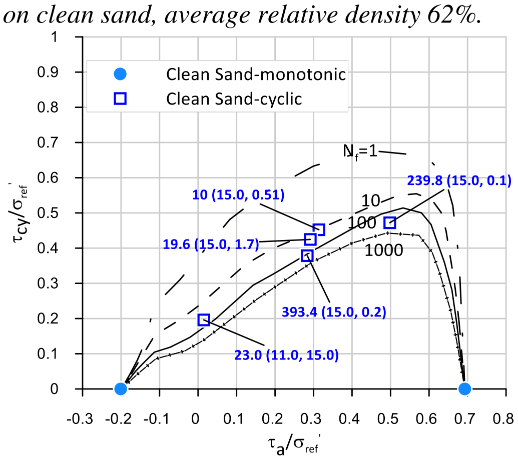
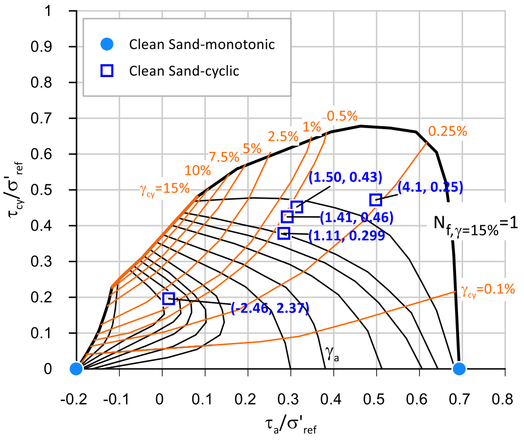


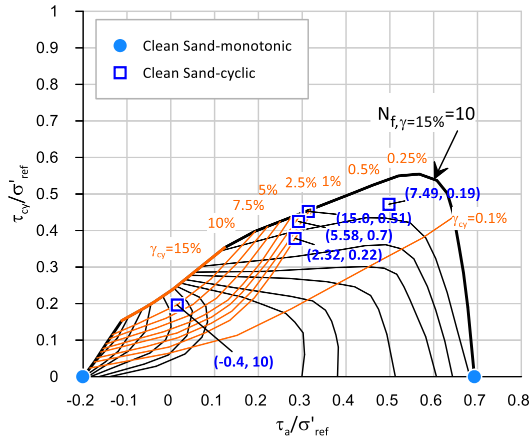
Figure 4b Failure contours on clean sand, average relative density 62%. Labels: $N_f(\gamma_a, \gamma_{cy})$



Average shear strain in extension side: -0.1%, -0.25%, -0.5%, -1%, -2.5%, -3.8% and -15%

Average shear strain in extension side: 0%, 0.1%, 0.25%, 0.5%, 1%, 2.5% and 15%

Figure 4c Normalized stresses and strains at N=1 on clean sands, average relative density 62%.



Average shear strain in extension side: -0.1%, -0.25%, -0.5%, -1%, -2.5%, -3.8% and -15%

Average shear strain in extension side: 0%, 0.1%, 0.25%, 0.5%, 1%, 2.5% and 15%

Figure 4d Normalized stresses and strains at N=10 on clean sands, average relative density 62%.

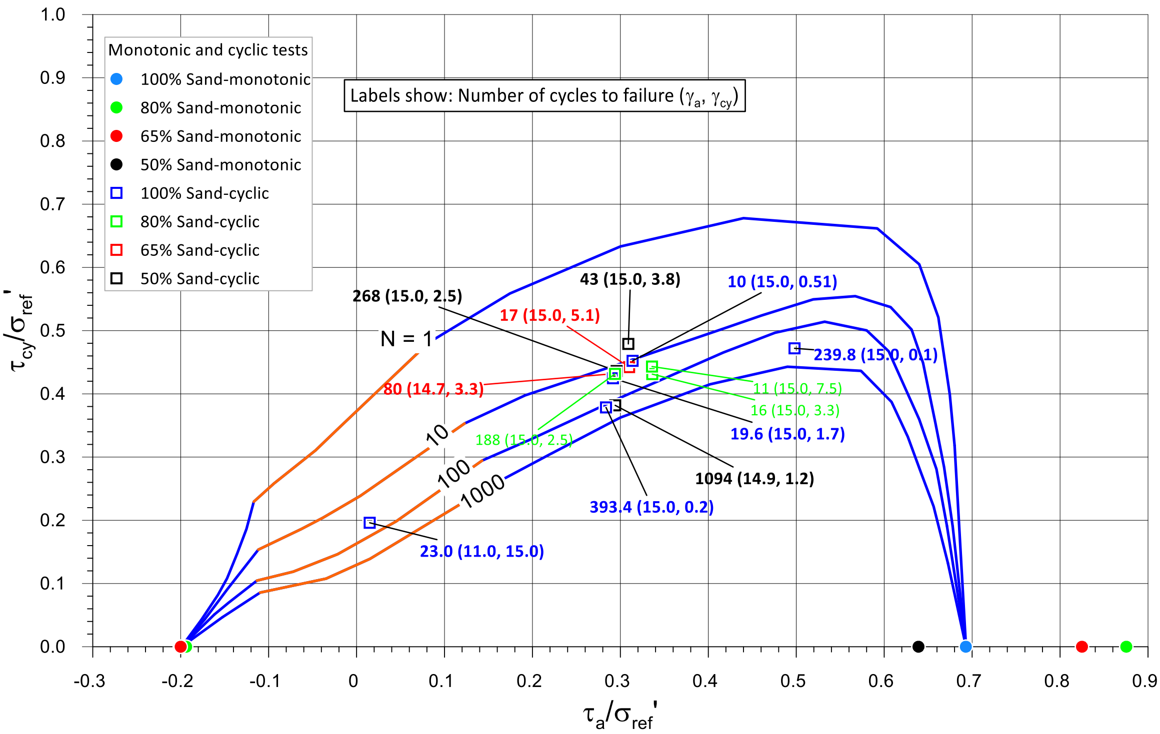


Figure 5 Failure contour diagrams, including all cyclic CAU tests in this study.

6 DISCUSSION AND CONCLUSION

This experimental study focused on behaviour of clean sand, sand and gravel mixtures by performing large size triaxial tests. Gravel contents varied as 0%, 20%, 35% and 50%. Test results indicated that static strength in compression is increasing when gravel content is increasing from 0% to 20% and 35%, however the compression strength is decreased when gravel content is increasing from 35% to 50%. There could be a transitional gravel content between 35% and 50%, where sand-dominant behaviour is changing to gravel dominant behaviour.

Complete cyclic contours were developed for clean sand, and all other test results on sand-gravel mixtures are given and compared in failure contours. At an average shear stress ratio about 0.3, cyclic strength for sand-gravel mixtures with 50% gravel content is the highest among all tested samples.

The conclusion in the paper is based on a limited number of tests and more experimental work is needed for further interpretation on behaviour of sand-gravel mixtures in the future.

AUTHOR CONTRIBUTION STATEMENT

Shaoli Yang: Data curation, Formal Analysis, Writing- Original draft. **Guoxiao Hu**: Performing tests **Rui Wang**: Supervision of lab testing **Ben He**: Funding acquisition, Reviewing and Editing,

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