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Evolution of elastic properties of granular soils under very large of number of multiaxial stress cycles

L'evolution des propriétés élastiques des sols granulaires sous un très grand nombre de cycles de contraintes multiaxiales

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ABSTRACT: Geotechnical structures, particularly in offshore locations, can be subjected to millions of loading cycles during their whole design life. The stress state of soil elements close to the foundation is also three-dimensional and rotation of principal stresses invariably occurs as the load is applied on the foundation. There is indeed an unanswered research question whether the soil mechanical properties evolve under such long-term complex loading conditions, with important consequences for the design of offshore geotechnical structures. The present research has investigated the effect of the application of a very large number of loading cycles on the elastic stiffness properties of a sub-angular silica sand (Hostun sand). The experimental work has been carried using a Hollow Cylinder Torsional Apparatus equipped with a very high-resolution local strain measurement system, composed of six non-contact displacement transducers (0.1 µm resolution) based on eddy current effect. Several sand samples were prepared under different initial densities and anisotropic stress level conditions, and then subjected to a large number of loading cycles. Evolution of both Young's and shear moduli has been mapped throughout the tests. It is shown that the material conserved its stiffness despite the application of more than half million of small loading cycles.

RÉSUMÉ: Certaines structures géotechniques, en particulier celles situées dans les milieux offshores, peuvent être soumises à des millions de cycles de chargement au cours de leur durée de vie. L'état de la contrainte des éléments du sol à la proximité des fondations est également multidimensionnel, et donc la rotation des axes de contraintes principales se produisent invariablement une fois qu'une charge est appliquée sur les fondations. Dans ces conditions de chargement complexe et à long terme, les propriétés mécaniques des sols peuvent évoluer avec de conséquences importantes pour le comportement des structures géotechniques offshore. Cette recherche étudie l'effet d'un très grand nombre de cycles de chargement irréguliers (à travers l'amplitude et l'orientation des axes principaux) sur les propriétés de la rigidité élastique d'un sable siliceux angulaire (sable d'Hostun). Le travail expérimental a été réalisé en utilisant un appareille de Cylindre Creux équipé d'un système de mesure de déformation avec une très haute résolution composée de six capteurs (non-contact), 0.1 µm de resolution, basés sur l'effet des courants de Foucault. Plusieurs échantillons de sable ont été préparés dans différentes conditions initiales de densité et de la contrainte anisotrope. L'évolution des modules de Young et de cisaillement a été suivie au cours de l'application des cycles de chargement. Il est montré que le matériau conserve sa rigidité malgré l'application de plus de la moitié d'un million de petits cycles de chargement.

KEYWORDS: Hollow Cylinder Torsional Apparatus, Multi-cyclic loading, Small strain, Elastic stiffness, Multiaxial stress path.

1 INTRODUCTION AND BACKGROUND

One of the leading criteria for the design of offshore structures is to ensure that their natural frequency does not fall within critical excitation frequency bands (Bhattacharya et al., 2013). The natural frequency of offshore monopile foundations is highly sensitive to the horizontal foundation stiffness, principally governed by the elastic stiffness properties of the surrounding soil. Under millions of cycles imposed during the operational lifetime of the offshore structure, the soil may densify, or in some circumstances possibly loosen, resulting in changes to the stiffness of the foundation-soil system. Any significant stiffness shift of the soil could move the system towards resonance. It is therefore important to assess the evolution of elastic stiffness of granular soil under very large number of loading cycles representative of the whole design life of offshore structures.

Previous soil element testing campaigns have investigated the effect of regular load cycles on the soil stiffness properties up to tens of thousand cycles (e.g. Wichtmann, 2005). Most of the experimental testing has also been performed in the conventional triaxial or simple shear apparatus where the orientation and eventual rotation of principal stress axes, typically occurring within a soil mass, can not be reproduced.

Instead, this paper will present the results of an ongoing experimental testing campaign aiming to investigate the evolution of the elastic Young's and Shear moduli of a granular soils subjected to a very large number of loading cycles with varying orientation of the principal stress axes. The investigation is performed using a Hollow Cylinder Torsional Apparatus (*HCTA*), which controls four stress components on a soil element and the principal stress directions. Accurate measurements of the quasi-elastic properties of the material were obtained using a local strain measurement system (Ibraim et al., 2011). Evolutions of both moduli under a sequence of a large amount of axial and torsional loading cycles (>10^5) will be presented here for different initial stress conditions.

2 MATERIAL AND TESTING DEVICE

2.1 *Hostun sand*

Hostun RF (S28) sand has been used in this study. It is a sub-angular to angular siliceous granular soil (SiO_2>98%) and its particle size distribution is reported in Figure 1. Its main physical properties are as follows: mean grain size D_{50}=0.32 mm, coefficient of uniformity C_u=1.70, coefficient of gradation C_g=1.1, specific gravity G_s=2.65 and minimum and maximum void ratios, respectively e_{min}=0.62 and e_{max}=1.00.

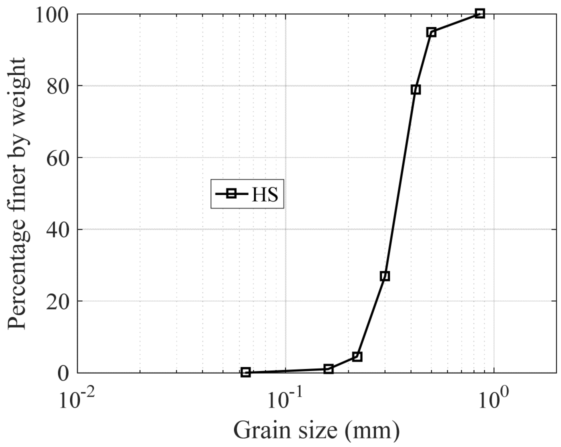

Figure 1 Grain Size Distribution, Hostun RF (S28) sand.

2.2 *Hollow Cylinder Torsional Apparatus*

The Bristol HCTA was employed to investigate the evolution of the elastic properties of Hostun sand under multiaxial cyclic stress loading condition. The apparatus controls the axial load (*W*), torque (*T*) and internal (P_i) and external pressure (P_o) independently (Figure 2a).

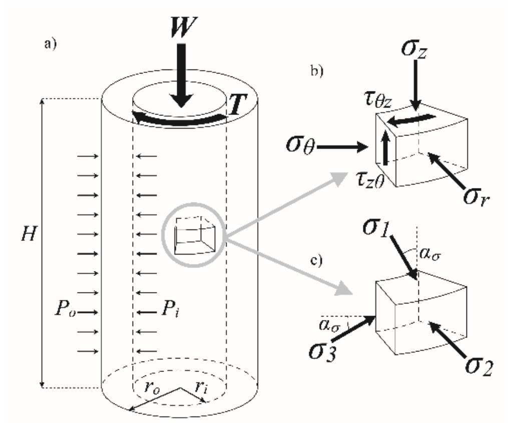

Figure 2 (a) Forces and pressures applied to the specimen and its main dimensions; (b) general stress state in a soil element and (c) principal stress components in a soil element.

The application of these enables the control of all the stress the components (σ_z, σ_r, σ_θ, $\tau_{\theta z} = \tau_{z\theta}$, Figure 2b) allowing the investigation of generalized stress paths which are characterised by four independent parameters: the mean principal effective stress (p'), the generalised deviatoric component of stress (q), the intermediate principal stress parameter (b) and the angle between the major principal stress σ_1 and the vertical direction (α_σ in Figure 2c).

2.3 *Small Strain Measurement System*

A general view of the local system of measurement of strains developed for the new hollow cylinder torsional apparatus is shown in Figure 3. The measurement system consists of six non-contact displacement transducers (based on eddy current effect) with a measurement range of 2 mm and a resolution of 0.1 µm. The vertical and circumferential displacements are measured in the central part of the sample using two pairs of non-contact transducers (S1 and S2, S3 and S4, respectively) fixed on stainless steel rods. The corresponding rectangular aluminium plate targets are fixed on two parallel aluminium rings positioned in the central section of the sample at a distance *Hc* of 100 mm (Figure 3). The rings are attached to the sample's external membrane by three flexible strips. The outer radial sample displacements are deduced by the average of the measurements given by two non-contact transducers (S5 and S6) pointing at aluminium foil targets placed on the sample's side of the outer membrane - in direct contact with the sand. The current inner radius changes have been calculated from the volume changes of the inner cell (corrected for the membrane penetration effects) combined with the vertical sample variations.

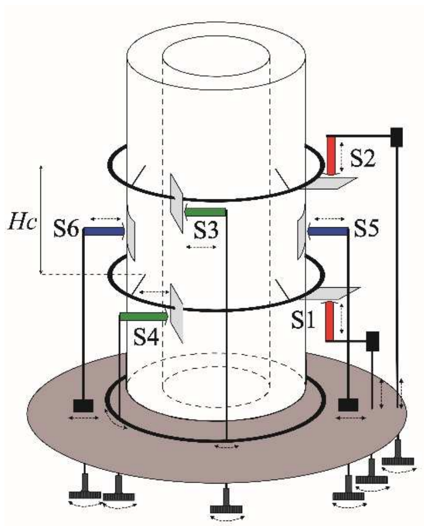

Figure 3 Small strain measurements system inside the hollow cylinder torsional apparatus cell.

In order to take advantage of the non-contact transducer's high resolution over a complete test and up to large strains, the transducers at different stages of the test have to be re-located, so the best accuracy for strains is maintained at various investigation points along the stress/strain paths. Therefore, technical solutions have been developed for each pair of the non-contact transducers (Ibraim et al., 2011) in order to allow the adjustment of their position from outside the confining cell (Figure 3).

The precisions with which the strains could be resolved are: 2×10^{-6} for axial strain, ε_z, 5×10^{-6} for radial strain, ε_r, 10^{-7} for circumferential strain, ε_θ, and 10^{-6} for shear strain, γ.

3 SAMPLE PREPARATION AND DIMENSIONS

The soil samples tested in the HCTA have a typical hollow cylindrical shape with an outer radius (r_o) of 50 mm, inner radius (r_i) of 30 mm and 200 mm height (*H* in Figure 2a). The geometry helps minimising the degree of stress and strain non-uniformities, inevitable in a hollow cylinder specimen as a result of the sample curvature and the restraint at its ends (Sayão & Vaid, 1991 and Hight et al., 1983).

The technique used to prepare hollow cylindrical samples consists of dry deposition and vibration. Dry sand was gently poured in between inner and outer membranes. The deposition funnel was lifted up whilst the sand level raised in order to maintain a constant zero fall height. Vibration (at a frequency of 55 Hz) was applied until the target fabrication void ratio was achieved. The sand samples were tested in fully saturated conditions which were ensured by the CO_2 flushing method together with the employment of water back pressure up to 300 kPa. Once saturated, the sample was subjected to an isotropic consolidation performed by manually increasing both the inner and outer cell pressure.

4 TESTING PROGRAMME

The experimental campaign has been divided in two phases: the first phase (Test Nos.1 to 4 in Table 1) focused on the effect of initial stress state and cyclic loading direction on the evolution of elastic stiffness of soil. The second phase explored the soil behaviour under a very large number of cycles (Test Nos.5 and 6).

Table 1 List of the performed tests where $\alpha_{\sigma,m}$ and $\alpha_{\sigma,c}$ stand for rotation of the principal stress axes during monotonic and cyclic loading respectively and e_0 is the initial void ratio.

Phase 1									
Test No.	e_0	$\alpha_{\sigma,m}$	$\alpha_{\sigma,c}$	*No. Cycles*					
				B	*C*	*D*	*E*	*F*	*G*
1	0.819	*0º,90º*	*0º,90º*	3240	2880	3240	3240	12240	3240
2	0.816	*0º,90º*	*±45º*	3240	6480	3780	3420	3330	16380
3	0.825	*±45º*	*±45º*	3780	3240	3240	3240	3240	3420
4	0.838	*±45º*	*0º,90º*	3240	3240	3240	3240	3240	3240

Phase 2				
Test No.	e_0	$\alpha_{\sigma,m}$	$\alpha_{\sigma,c}$	*No. Cycles*
5	0.816	*45º*	*0º,90º*	200000
6	0.807	*0º*	*±45º,0º,90º*	550000

The first four tested samples (Test Nos.1 to 4) were subjected to a range of deviatoric stress states which are represented in Figure 4 in the $\tau_{z\theta}/p'$ - $(\sigma_z-\sigma_\theta)/2p'$ plane. The mobilised friction angle (φ'_m) for each deviatoric stress level is also indicated in the figure. Test Nos.1 and 2 were loaded to pure compression/extension loading states ($\alpha_{\sigma,m}$=0, 90º) before applying each sequence of cyclic loads, while Test Nos.3 and 4 were subjected to pure torsion ($\alpha_{\sigma,m}$=±45º) to achieve the desired pre-cycle deviatoric stress state. At each point *B*, *C*, *D*, *E*, *F* and *G* in Figure 4, the sample was subjected to small amplitude deviatoric stress cycles (q_{ampl}=±5 kPa) in either compression/extension ($\alpha_{\sigma,c}$=0, 90º) or torsional ($\alpha_{\sigma,c}$=±45º) modes. The number and type of the cyclic loading for each sample at each stress state are summarised in Table 1.

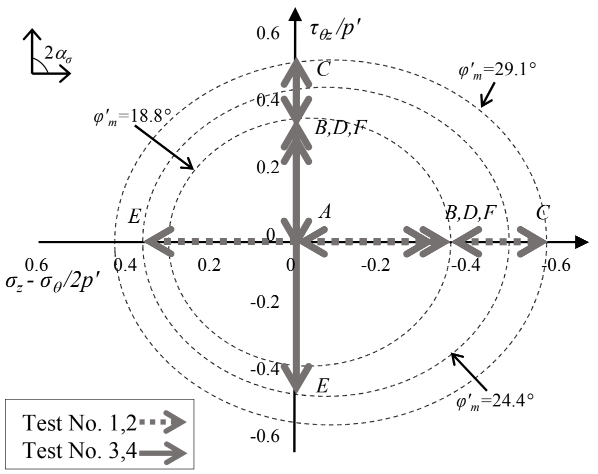

Figure 4 Imposed stress path in the normalised shear stress-deviatoric stress plane. Mobilised friction angles (φ'_m) and rotation of the stress axes (α_σ) are reported.

Measurements of the Young's and Shear moduli (E_z and $G_{\theta z}$, respectively) were taken at the beginning and at end of each cyclic loading stage (*B*, *C*, *D*, *E*, *F* and *G* in Figure 4), over 10 small axial or torsional cycles. Example of stiffness moduli evaluated through the slope of stress - strain curves, with the strains measured by the local measurement systems, are shown in Figure 5.

The second part of the testing programme investigates the effect of very large number of cycles (up to 0.55 millions) on the sand elastic properties (Test Nos.5 and 6 in Table 1). The samples were initially subjected to a compressional load in $\alpha_{\sigma,m}$ = 0º direction for Test No. 6 or pure torsion ($\alpha_{\sigma,m}$ = 45º) for Test No. 5 reaching the deviatoric stress in stage *B* (Figure 4). Then a large number of small amplitude loading cycles were applied for a long period of time during which the effects of amplitude and direction of the cyclic loading were investigated. A loading frequency of 0.05 Hz was kept constant throughout the tests. Evolution of the sample stiffness was monitored at regular intervals (at approximately each 10^4 cycles).

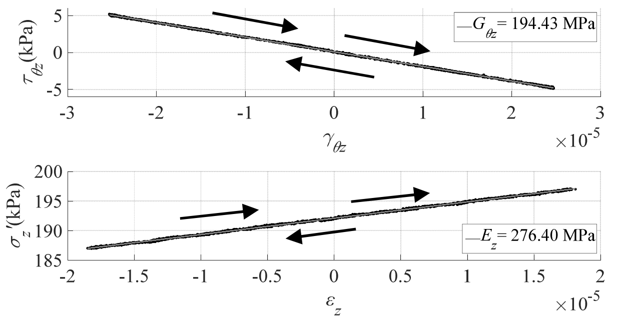

Figure 5 Stress-strain relationship for a single cycle of q_{ampl}=±5 kPa: axial direction (a) with relative Young's modulus (E_z) and torsional direction (b) with shear modulus ($G_{\theta z}$).

5 TEST RESULTS

As previously mentioned, small strain sample stiffnesses were measured at various investigation points in order to detect variations throughout the tests. A summary of the results for Test Nos. 1 to 4 of the testing Phase 1 are reported in Figure 6, as ratio between initial ('*i*') and final ('*f*') shear and Young's moduli measured, at the beginning and at the end of each cyclic loading stage (*B*, *C*, *D*, *E*, *F* and *G* in Figure 4).

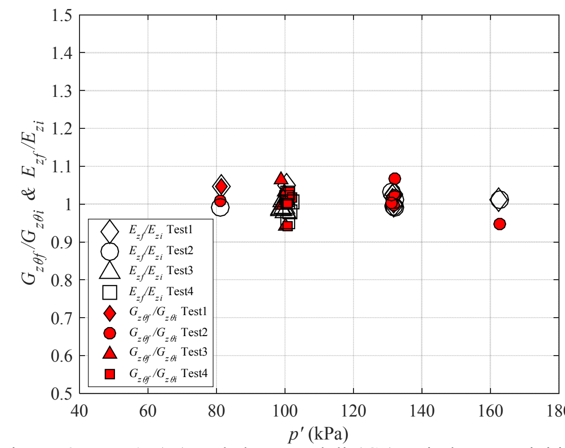

Figure 6 Young's (E_z) and shear moduli ($G_{\theta z}$) ratio between initial and final investigation points from Test Nos.1 to 4.

For the number of small amplitude cycles applied, the stiffness values, E_z and $G_{\theta z}$, were found to be essentially unchanged for the whole range of stresses and loading directions imposed. Results show variations of stiffness within 10% from the initial values; in most cases within only few percent which may be linked to a slight densification or to some inherent variability of the measurements.

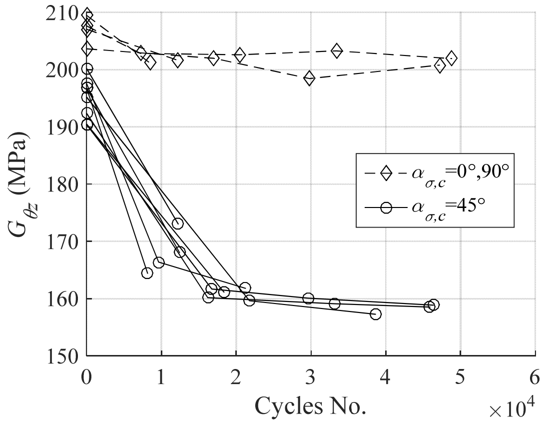

Figure 7 Shear modulus $G_{z\theta}$ decay with the number of cycles for each loading stage (Test No.6).

For Test No. 6, the specimen was subjected to more than half a million of torsional ($\alpha_{\sigma,c}$=±45º) and axial ($\alpha_{\sigma,c}$=0º, 90º) cycles (about 20-40 times the number of cycles applied in Test Nos.1 to 4). The initial idea was to perform continuous and uninterrupted small amplitude cycling for the whole test duration (more than 9 months). However, interruptions of the hydraulic loading supply unavoidably happened and under these conditions the sample was automatically unloaded to an isotropic state and then slowly reloaded to the desired pre-cyclic stress level. After reloading, creep deformations were allowed to exhaust before taking any stiffness measurement.

Figure 7 presents $G_{\theta z}$ measurements of each cyclic loading sequence between unloading-reloading interruptions. The number of cycles was zeroed at each interruption for this plot. The data reveal the influence of cyclic loading direction ($\alpha_{\sigma,c}$) on the stiffness trend ($G_{\theta z}$) within each sequence of loading cycles. In particular:

1) for torsional ($\alpha_{\sigma,c}$=±45º) cycles, there is a repeatable decreasing trend to apparently a stable shear modulus ($G_{\theta z}$) reached within the first 20000 cycles. The drop is about 20% the value at the start of the cyclic sequence;

2) for axial ($\alpha_{\sigma,c}$=0º, 90º) loading cycles, there is only a very limited (about 2-3%) drop of shear stiffness.

The evolution of the initial Young's and shear moduli for each loading sequence during the whole Test No.6 is reported in Figure 8. The increase in stiffness eventually reach about a 9% compared with the initial measurements for both Young's and shear moduli. This was not associated with considerable variation in void ratio. It may be that the unloading-reloading loop could cause a spatial grain arrangement within the soil matrix producing a stiffer structure of the sample. However the fabric build up is only temporary: the results in Figure 7 have shown that after $1.5 \cdot 10^4$ to $2 \cdot 10^4$ cycles the stiffnesses tend to stabilise around a given value, which depend on the direction of the applied loading.

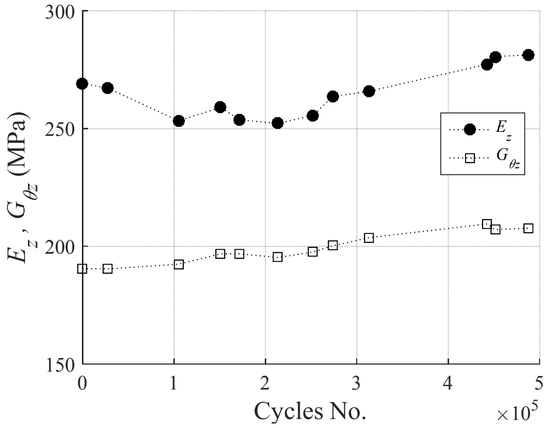

Figure 8 Initial E_z and $G_{z\theta}$ for each stage throughout Test No.6.

6 CONCLUSION

The evolution of the main elastic properties (E_z, $G_{z\theta}$) of Hostun sand under very large numbers of small amplitude compression/extension and torsional cycles has been investigated in this research, using a HCTA and a local small strain measurement system. Two types of tests were performed.

In the first series of tests which involved the application of a few thousand compression/extension and torsional small amplitude cycles, negligible variations of stiffness were observed.

In the second series of tests which involved the application of up to half million cycles (mostly torsional cycles), in batches of few tens of thousands of cycles because of periodic unavoidable system interruptions, the following observations have been made:

i) There is a repeatable decreasing trend of shear stiffness within each sequence of loading cycles. The stiffness drops to a constant value of about 80% of its initial value before reaching about 20000 cycles for torsional cycles. This drop was only 3% for compressive loading cycles.

ii) The initial value of stiffness before each loading sequence increases as the test proceeds. This may be the result of fabric changes during large unloading-reloading loops at each interruption.

iii) The build-up in initial stiffness appears to be only temporary and it is erased by the application of thousands of small amplitude cyclic loadings. The stabilised value of stiffness for each cyclic sequence does not seem to change for the 0.55 million of cycles applied.

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