Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-672

Triaxial cyclic behaviour of calcareous sand for offshore energy applications

Comportement cyclique triaxi al du sable calcaire pour les applications énergétiques offshore

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ABSTRACT: Soils in the vicinity of the foundations of offshore energy systems are subjected to cyclic stresses arising from repeated environmental loads. Long-term application of such loading alters the surrounding soil's strength and deformation characteristics and subsequently may put the performance of such systems at risk. The deformation of soil i.e., strain accumulation depends on both the soil parameters and the loading conditions. This paper presents the findings from an experimental study that focuses on strain accumulation in calcareous sands subjected to long-term cyclic loading. A series of drained cyclic triaxial tests were performed on saturated calcareous sand specimens up to 10,000 loading cycles. The influence of cyclic stress amplitude and sand density on the strain accumulation is investigated. The experimental results show an increase in strain accumulation with increasing cyclic stress amplitude and void ratio. The formulations of the High Cycle Accumulation Model are calibrated based on the experimental results. The test results provide valuable information on the deformation characteristics of the calcareous sands, which can be used to predict the performance of offshore structures under cyclic loads. The triaxial test results also provide a very useful database for calibrating advanced soil models to accurately assess the performance and behavior of the foundations of offshore energy systems.

RÉSUMÉ: Les sols à proximité des fondations des systèmes d'énergie offshore sont soumis à des contraintes cycliques résultant des charges environnementales répétées. L'application à long terme de ces charges altère la résistance et les caractéristiques de déformation du sol environnant, mettant potentiellement en danger la performance de ces systèmes. La déformation du sol, c'est-à-dire l'accumulation de contrainte, dépend à la fois des paramètres du sol et des conditions de chargement. Cet article présente les résultats d'une étude expérimentale axée sur l'accumulation de contrainte dans des sables calcaires soumis à un chargement cyclique à long terme. Une série d'essais triaxiaux cycliques drainés a été réalisée sur des échantillons de sable calcaire saturé jusqu'à 10 000 cycles de chargement. L'influence de l'amplitude de contrainte cyclique et de la densité du sable sur l'accumulation de contrainte est étudiée. Les résultats expérimentaux montrent une augmentation de l'accumulation de contrainte avec l'augmentation de l'amplitude de contrainte cyclique et du rapport de vides. Les formulations du modèle d'accumulation en haute fréquence sont calibrées en fonction des résultats expérimentaux. Les résultats des essais fournissent des informations précieuses sur les caractéristiques de déformation des sables calcaires, pouvant être utilisées pour prédire la performance des structures offshore sous des charges cycliques. Les résultats des essais triaxiaux fournissent également une base de données très utile pour calibrer des modèles avancés de sol afin d'évaluer avec précision la performance et le comportement des fondations des systèmes d'énergie offshore.

Keywords: Calcareous sand; cyclic stress ratio; strain accumulation; long-term drained response.

1 INTRODUCTION

Offshore wind turbine (OWT) foundations are subjected to environmental loadings during their life span of approximately 25 to 30 years. The response of OWT foundations is influenced by the loading characteristics and the soil conditions around the foundation. During extreme events such as storms or earthquakes, the high-amplitude cyclic loads (strain amplitudes $\varepsilon^{ampl} > 10^{-3}$) can induce undrained soil behaviour. This can lead to the rapid development of excess pore pressure, posing a potential risk of liquefaction.

Under regular operational loads of small amplitude ($\varepsilon^{ampl} < 10^{-3}$), as indicated by Wichtmann et al. (2005), the excess pore water pressure dissipates, and the soil behaves in a drained fashion. However, the soil behaviour may exhibit variability across different loading frequencies and soil permeability. The cyclic loading results in hysteresis loops that are not perfectly closed leading to strain accumulation in the soil, commonly referred to as "ratcheting" (Houlsby et al., 2017). The ratcheting is a primary concern for long-term serviceability. It is responsible for settlements that can compromise the operation of the OWTs. Therefore, it is crucial to account for both the short-term undrained behaviour under extreme loads, as well as the long-term cyclic response, in the design of such foundations.

Standards and codes i.e. API (2000), and DNV (2004) provide design guidelines for typical silica sands. In the presence of calcareous sands, there is limited available knowledge due to their susceptibility to crushing (Salem et al., 2021). This becomes of increasing importance considering that calcareous sands are commonly found in the marine environment in Europe and around the globe (e.g., Southern Mediterranean Sea, the Persian Gulf, Brazil, and Australia) (Spagnoli & Doherty, 2016). The physical properties of calcareous sands are different to silica sands (Cao et al., 2020; Shi et al., 2021). The calcareous sand is formed of marine biological debris mainly composed of calcium carbonate. The particles are irregular in shape, and flaky and porous which make it prone to breaking under loading (Ding et al., 2021).

Strain accumulation in calcareous sand under long-term cyclic loading is far more limited. Jafarian & Javdanian, (2020) examined the cyclic behaviour of calcareous vs silica sands, finding that for calcareous sand, increasing effective stress led to higher shear modulus and lower damping ratio compared to silica sand. The differences were attributed to the contrasting grain shape, mineralogy, and texture of calcareous sand. Similar behaviour was also reported by Yu, (2017). Jafarian et al., (2018) compared small-strain dynamic characteristics of calcareous and silica sands. It was found that the small-strain shear modulus of calcareous sand is more affected by mean effective confining pressure than the silica sands.

This paper investigates the cyclic behaviour of calcareous sand subjected to 10,000 loading cycles. To explore the influence of stress amplitude and density state, triaxial tests have been performed at selected densities and stress amplitudes. In addition, the results are used to calibrate the High Cycle Accumulation (HCA) model parameters.

2 HIGH CYCLE ACCUMULATION MODEL

To predict the strain accumulation at a high number of loading cycles ($N \geq 1000$), Niemunis et al., (2005) proposed the High Cycle Accumulation (HCA) model. The HCA model calculates the strain accumulation by combining two different numerical strategies. They are referred to as the *implicit* (low cycle) model and the *explicit* (high cycle) model of calculation. In the *implicit* model each cycle is calculated with hundreds of small increments and the accumulation appears as a by-product due to the not perfectly closed stress or strain loops. In the explicit model, the first two cycles are calculated conventionally with strain increments. The strain accumulation due to the following cycles is calculated using a direct (explicit) formula (Figure 1).

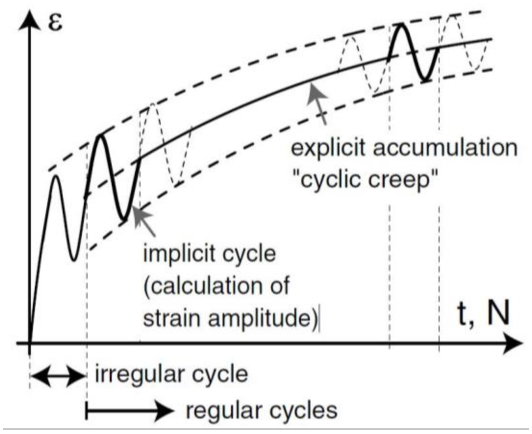

Figure 1. Calculation procedure of explicit models (Wichtmann et al., 2005).

According to the HCA model, the rate of strain accumulation can be calculated as the product of six functions (Table 1):

$$\varepsilon^{acc} = f_{ampl}\, f_N\, f_e\, f_p\, f_Y\, f_\pi \tag{1}$$

Table 1 Summary of the functions, and material constants of the high-cycle model (Wichtmann et al., 2015)

Function	Const.
$f_{\mathrm{ampl}} = \left(\varepsilon^{\mathrm{ampl}}/10^{-4}\right)^{C_{\mathrm{ampl}}}$	C_{ampl}
$\dot{f}_N = \dfrac{C_{N1}C_{N2}}{1+C_{N2}N} + C_{N1}C_{N3}$	C_{N1}, C_{N2}, C_{N3}
$f_p = \exp\left[-C_p\ (p^{\mathrm{av}}/(100\ \mathrm{kPa}) - 1)\right]$	C_p
$f_Y = \exp\left(C_Y\ \bar{Y}^{\mathrm{av}}\right)$	C_Y
$f_e = \dfrac{(C_e - e)^2}{1+e}\ \dfrac{1+e_{\max}}{(C_e - e_{\max})^2}$	C_e

Each function considers distinctly the influence of different parameters that is strain amplitude (f_{ampl}), cyclic preloading history (f_{N}), void ratio (f_{e}), average stress (f_{p}), average stress ratio (f_{Y}), and polarization changes (f_{π}). The material constants of the functions can be obtained from drained cyclic triaxial test series. A minimum of three sets of tests are required to obtain such constants: C_e requires tests with different void ratios, keeping the same average stress and stress amplitude. C_p requires tests with different average mean pressure, under constant void ratios and average stress ratios. C_Y requires tests with different average stress ratios, under constant void ratios, average mean pressure, and stress amplitude.

Wichtmann et al. (2010) calibrated the HCA model parameters using results obtained from triaxial test results on eight different quartz sand. Further, Benoot et al. (2014) calibrated the model from cyclic tests on silica sand. However, the predictive capabilities of the HCA model had not been assessed for calcareous sands. Calcareous sands have some distinctive features, such as high void ratio, carbonate content, and crushability.

3 METHODOLOGY

3.1 Test material

The calcareous sand tested in this study was taken from a reclaimed site in the Persian Gulf. The particle size gradation of the calcareous sand is illustrated in Figure 2. The index properties are summarized in Table 2 (Shi et al., 2021), while the mean particle size (d_{50}) of the sand used in this study is much higher than for typical silica sands encountered in offshore wind projects. Figure 3 shows the grain morphology: the particles are thin, irregular, and extremely flaky, which makes them prone to breakage, and gives them an irregular shape, with some having round structures. The rough texture of the particles and the presence of more void spaces make it a highly compressible material when subjected to shearing.

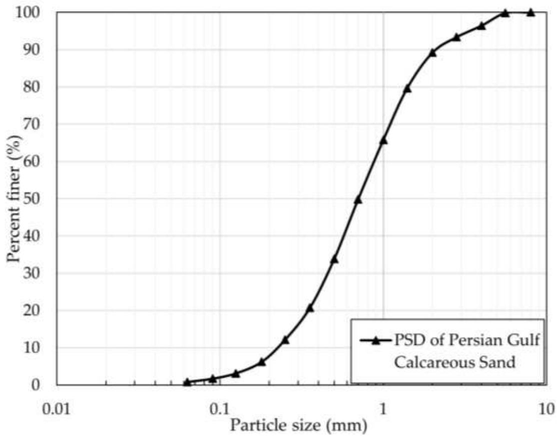

Figure 2. Particle size gradation of calcareous sand.

Figure 3. Grain morphology of calcareous sand (Shi et al., 2021).

Table 2 Basic physical and mechanical properties of calcareous sand

Property	Calcareous sand
Specific Gravity ($\boldsymbol{G_s}$)	2.81
Maximum void ratio ($\boldsymbol{e_{max}}$)	1.21
Minimum void ratio ($\boldsymbol{e_{min}}$)	0.75
Coefficient of uniformity ($\boldsymbol{C_u}$)	3.89
Mean particle size ($\boldsymbol{d_{50}}$) (mm)	0.68

3.2 Triaxial apparatus

An electromechanical dynamic triaxial apparatus was used. This apparatus is comprised of pressure/volume controllers that provide cell pressure and back pressure. It includes a submersible load cell to measure the axial stress, as well as sensors for measuring displacements, and pore pressures. All components were calibrated before conducting tests.

3.3 Testing procedure

Cylindrical specimens of 50 mm in diameter and approximately 100 mm in height were tested. Soil specimens were prepared using the water pluviation technique. A pluviator equipped with five steel wire strainers, which was specifically designed to ensure the even distribution of soil particles (Figure 4) was used. To achieve the targeted relative density and avoid sand particle breakage during the specimen preparation, the tapping of the mould from outside was employed by gently tapping the sides of the mould with a rubber hammer. Latex membranes with a thickness of 0.35 ± 0.01 mm were used.

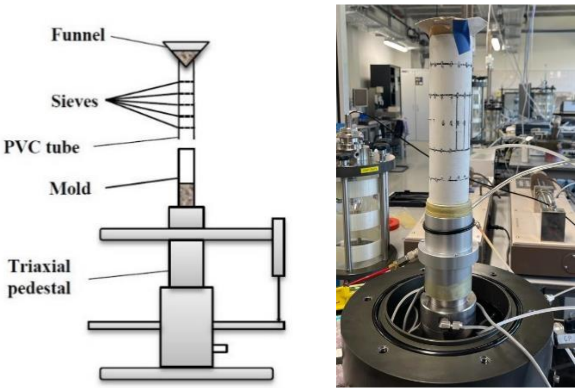

Figure 4. Water pluviation technique: (a) Schematic of pluviator, (b) pluviator with strainers used.

The specimens were saturated by flushing with de-aired water for 30 minutes and applying a back pressure of 700 kPa from 16 h to 24 h, to achieve the B-value higher than 0.95. In pre-experiment trials, it was required to apply such a high back pressure of 700 kPa to saturate the calcareous sand specimens, which was also adopted by Shi et al., (2021) using the same sand. After the saturation, the specimens were anisotropically consolidated ($K_o = 0.5$) to 100kPa initial mean effective stress levels. K_o consolidation was performed by using the Back Volume Change Measurement module in the GDS lab software. This back volume measurement is used to calculate the theoretical new height the specimen should attain to compensate for changes in volume while keeping the diameter constant.

Table 3 summarizes the stress-controlled drained triaxial tests with 10,000 load cycles conducted at a frequency of 0.5 Hz. The loading frequency of 0.5 Hz was selected based on the expectation that it would produce drained conditions based on previous studies (Ding et al., 2021; Witchmann et al., 2010). However, small fluctuations in pore water pressure of up to ±7 kPa were observed in selected tests in this study but were considered negligible relative to mean effective stress. It is also worth noting that loading frequency has minimal impact on sand deformation up to 1 Hz (Witchmann et al., 2010).

Table 3 Summary of the drained triaxial testing program.

Test ID	Void ratio	CSR= $q/2p'$	q_{ampl} (kPa)
1- CKDC	0.86	0.2	58
2- CKDC	0.89	0.2	58
3- CKDC	0.87	0.3	80
4- CKDC	0.89	0.2	58
5- CKDC	0.79	0.2	58
6- CKDC	0.79	0.3	80

4 RESULTS AND DISCUSSION

4.1 Accumulation of strain with number of cycles

Accumulation of strain with the number of cycles in sand samples subjected to cyclic loading is illustrated in Figure 5. Under cyclic loading the total strain develops in the soil sample, consisting of both recoverable (elastic) and non-recoverable (plastic/residual) components. Initial hysteresis loops showed primarily elastic behaviour with minimal plastic strain component. However, with further load cycles hysteresis loops deviated from the initial path, indicating a rise in plastic strains. The results also showed that the residual axial strain develops gradually with each additional loading cycle.

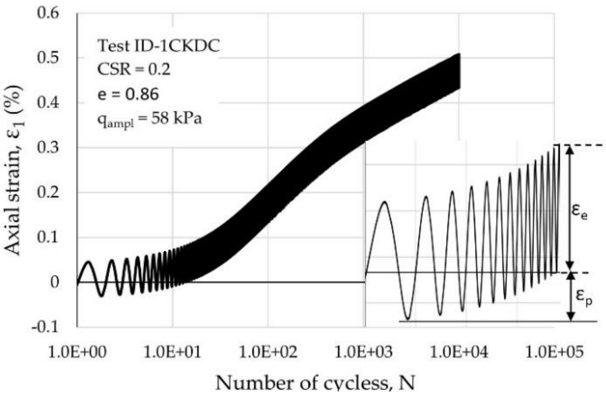

Figure 5. Axial strain progression with number of cycles, N.

4.2 Effect of cyclic stress ratio

Figure 6 presents the development of axial strain (ε_1^{acc}) versus the number of cycles (N). Four tests were conducted under selected void ratios (medium dense 0.89 and dense 0.79) and selected CSR (0.2 and 0.3). At the starting phase, a similar strain development was observed in all the curves and then, the rising rate of strain accumulation varied depending on the test conditions. For the denser specimen (tests 5 and 6), increasing the CSR from 0.2 to 0.3 resulted in higher strain accumulation. This occurred as the larger cyclic stresses induced greater deformations with each cycle. A similar trend has been observed in the medium-dense soil specimens (tests 1 and 3). Overall, as anticipated, denser specimens exhibited lower accumulated strains than looser samples under similar CSR.

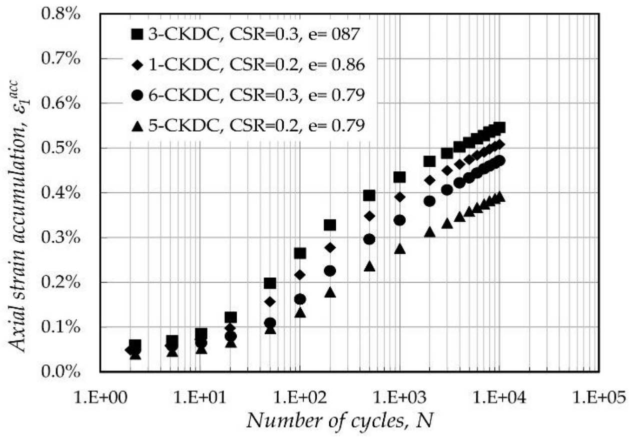

Figure 6. Axial strain accumulation with the number of cycles N in tests with different CSRs.

4.3 Effect of void ratio

Figure 7 plots the axial strain accumulation (ε_1^{acc}) as a function of the number of cycles (N). To investigate the influence of the relative density on the strain accumulation, four drained tests were performed. Tests 2 and 4 were performed under identical conditions to verify the repeatability of the test data.

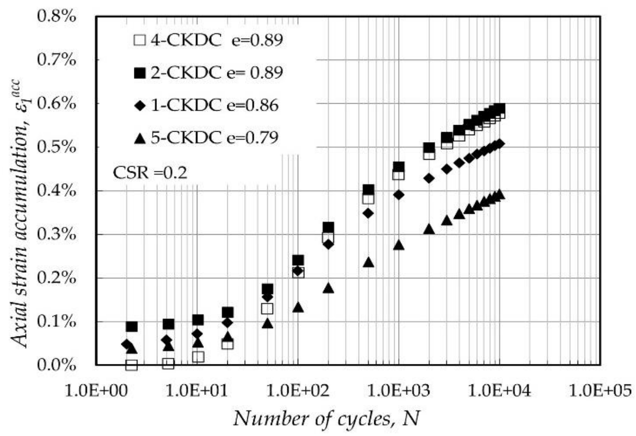

Figure 7. Axial strain accumulation with the number of cycles N in tests with varying void ratios.

A similar trend is observed for all samples in terms of strain accumulation. However, samples with higher void ratios exhibited greater accumulation of residual axial strain. Higher strain accumulation in samples with higher void ratios can be attributed to their ability to accommodate more grain arrangements under cyclic loading.

4.4 Calibration of HCA model functions

To eliminate the influence of strain accumulation on void ratio and strain amplitude, two out of six HCA model functions are used to normalize the measured strain accumulation. Function f_{ampl} accounts for the dependence of strain amplitude on the strain accumulation rate. Functions f_e accounts for the influence of the initial void ratio on the strain accumulation. In f_{ampl} and f_e functions the material constants C_{ampl} = 2 and C_e = 0.58 are determined employing non-linear regression analysis, using reference strain $\varepsilon_{ref}=10^{-4}$ and reference void ratio e_{ref}= e_{max}=1.21. Figure 8 and 9 show the normalized measured residual axial strain curves by f_{ampl} and f_e functions.

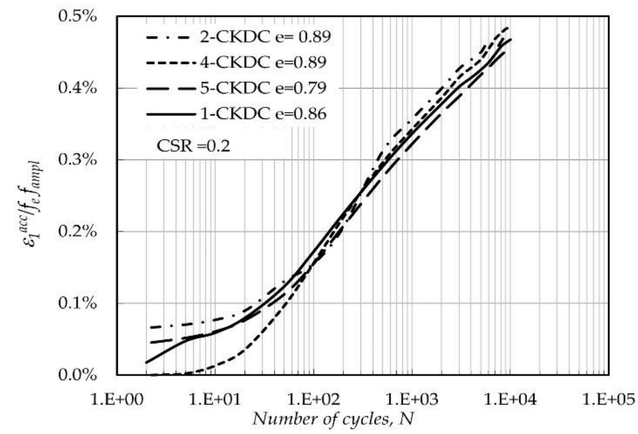

Figure 8. Normalized accumulated axial strain as a function N with different void ratios.

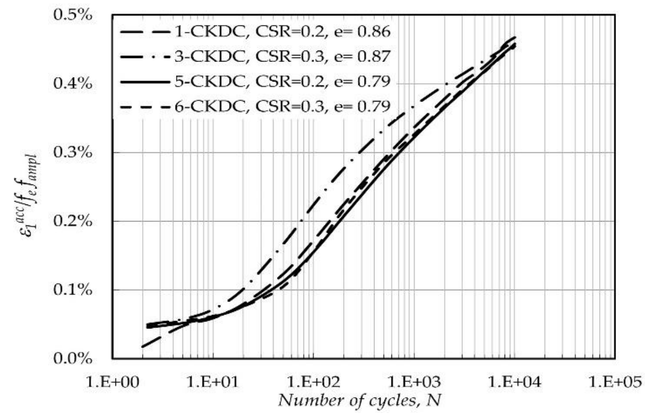

Figure 9. Normalized accumulated axial strain as a function of N with different CSRs and void ratios.

The close alignment of normalized curves suggests a close correspondence in strain accumulation behaviour. The normalization process effectively eradicated the influence of different test parameters on the strain accumulation behaviour. This suggests the HCA model functions i.e. f_{ampl} and f_e could be applied for calcareous sand, despite the Wichtmann framework being developed for silica sand.

5 CONCLUSIONS

The accumulation of strain in calcareous sand under cyclic loading was explored through a series of drained cyclic triaxial tests. The accumulated strains were normalized using the HCA model functions to facilitate comparisons across varying test conditions. The following main findings are reported:

(1) With increasing the CSR higher strain accumulation was observed. This occurred as the larger cyclic stresses induced greater deformations with each loading cycle.

(2) The strain accumulation depends strongly on the soil density. Medium dense samples ($e = 0.86, 0.87, and\ 0.89$) exhibit higher axial strains than the denser sample ($e = 0.79$).

(3) The HCA model's functions f_e and f_{ampl} are calibrated for the calcareous sand, yielded material constants $C_{ampl} = 2$ and $C_e = 0.58$. These functions were used to normalize the accumulated strain. This allowed a meaningful comparison of strain accumulation trends between tests with varying conditions. The normalization process effectively suppressed the influence of different parameters on the strain accumulation.

ACKNOWLEDGEMENTS

This research was supported by the *Cyclic soil-structure interaction framework for the foundations of offshore renewable energy structures* project, funded by the “KU Leuven Global PhD Partnerships with The University of Melbourne” scheme (GPUM/21/023) and “The University of Melbourne Chancellery Strategic International Research Collaboration funds”. The authors would like to thank the Department of Mobility and Public Works (MOW) and Geotechniek Vlaanderen for providing access to the Persian Gulf sand and triaxial apparatus.

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