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

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-628

ECSMGE 24
XVIII EUROPEAN CONFERENCE ON SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

Assessment of soil constitutive models to predict the response of offshore wind turbines subjected to lateral cyclic loads

Évaluation des modèles constitutifs des sols pour prédire la réponse des éoliennes offshore soumises à des charges cycliques latérales

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ABSTRACT: Monopiles are the frequently used foundation types for offshore wind turbines (OWTs) to withstand the cyclic loads from wind and waves ensuring safe and reliable operation. Under such cyclic loads, strain accumulation occurs while the soil undergoes repeated loading and unloading cycles throughout the OWT's lifespan. Such a mechanism, referred to as "ratcheting", causes changes in soil properties and affects the performance of the OWT. Large accumulative displacements and rotations can cause fatigue damage and serviceability problems which may result in structural failure and operational disruptions. While a wide range of methods is available to predict the monotonic monopile response, limited advanced soil models are available to capture the complex mechanism of cyclic strain accumulation. Such models have different levels of accuracy, complexity, and parameter calibration process. Prior to assessing any boundary value problem, it is important to evaluate the performance of the soil constitutive models at the soil material level. This work presents a comparative numerical study of two state-of-the-art constitutive models for sands i.e., SANISAND-MS and PM4SAND, under triaxial test conditions via OpenSees and PLAXIS. A discussion on the model parameters, analysis settings, and the effect of the number of cycles in the response is presented.

RÉSUMÉ: Les monopieux sont les types de fondations fréquemment utilisés pour les éoliennes offshore afin de résister aux charges cycliques dues au vent et aux vagues, garantissant ainsi un fonctionnement sûr et fiable. Sous de telles charges cycliques, une accumulation de contraintes se produit pendant que le sol subit des cycles répétés de chargement et de déchargement tout au long de la durée de vie de l'éolienne. Un tel mécanisme, appelé "ratcheting", provoque des changements dans les propriétés du sol et affecte les performances de l'éolienne. De grands déplacements et rotations cumulatifs peuvent causer des dommages par fatigue et des problèmes de service qui peuvent entraîner une défaillance structurelle et des interruptions opérationnelles. Bien qu'une large gamme de méthodes soit disponible pour prédire la réponse monotone des monopieux, il existe peu de modèles avancés de sol pour capturer le mécanisme complexe d'accumulation de déformations cycliques. Ces modèles ont différents niveaux de précision, de complexité et de processus d'étalonnage des paramètres. Avant d'évaluer tout problème de valeur limite, il est important d'évaluer les performances des modèles constitutifs du sol au niveau du matériau du sol. Ce travail présente une étude numérique comparative de deux modèles constitutifs de pointe pour les sables, à savoir SANISAND-MS et PM4SAND, dans des conditions d'essai triaxial via OpenSees et PLAXIS. Une discussion sur les paramètres du modèle, les paramètres d'analyse et l'effet du nombre de cycles sur la réponse est présentée.

Keywords: Monopiles; cyclic lateral loads; strain accumulation; constitutive models for sands.

1 INTRODUCTION

Soil constitutive models describe the mechanical behavior of soils by defining the entire incremental stress-strain response under different loading conditions. The description of the soil behavior is particularly important for sands surrounding OWT monopiles. The pore water pressure buildup increases and affects cyclic mobility (Wichtmann et al. 2019). The strain accumulates resulting in tilting of OWTs and affecting structures' fatigue life (Liu et al., 2019).

Single element tests are commonly used to calibrate and verify soil constitutive models. Assessment of these models on their predictive capability of element tests gives an intuition about their use in boundary value problems (Duque et al., 2021). Wichtmann et al. (2019) and Duque et al. (2021) inspected triaxial simulations of different soil models on Karlsruhe fine sand (KFS). Both studies have concluded that there were deficiencies in accurately replicating some important attributes, such as pore pressure reproduction and accumulation of plastic strains. Since the results showed relative density (D_r) dependence, it is inferred that the bounding surface cannot be adequately characterized solely by the mean effective stress and void ratio for all stress-strain paths. Duque et al. (2021) claimed that a comprehensive model capable of addressing all these challenges has yet to be developed.

This paper compares the predictive power of two cutting-edge soil constitutive models: SANISAND-MS (Liu et al., 2019) and PM4SAND (Boulanger and Ziotopoulou, 2015) with SANISAND04 (Dafalias and Manzari, 2004) by numerical simulations of triaxial tests in OpenSees (Zhu et al., 2018) and PLAXIS (Bentley, 2020). The objective of the paper is to obtain insights for practical offshore foundation applications by gaining a deeper understanding of the capabilities and limitations of these models to capture strain accumulation at long-lasting cyclic loading events.

2 TRIAXIAL SIMULATION

An 8-node hexahedral linear isoparametric fully coupled *u-p* element with a single point integration point (SSPbrickUP) is used for effective stress analyses in saturated soils. Rayleigh damping with $\mathbf{C} = 0.05\,\mathbf{M} + 0.00032\,\mathbf{K}$ is defined to damp out the waves. For the shearing, each cycle is comprised of compression (1/4 of a full cycle), extension (2/4 of a full cycle), and compression again (1/4 of a full cycle). Cyclic loading continues until the predefined number of loading cycles is reached.

SANISAND04 is the first member of the SANISAND family. SANISAND-MS includes a memory surface to better control large strains. PM4SAND is formulated under plane strain conditions and features a revised fabric formation requiring three primary model input parameters: G_0, h_{p0}, and D_r, which are most important for model calibration. Secondary parameters are set to default values, which typically align with observed trends.

KFS was extensively tested in monotonic/cyclic, drained/undrained triaxial test conditions by Wichtmann and Triantafyllidis (2016). The soil model parameters calibrated in former studies are held for the comparison study (Wichtmann et al., 2019 for SANISAND04 and Liu et al., 2019 for SANISAND-MS). Although these models share 13 parameters in their model formulation, it is observed in the literature that model parameters for the same sand might be calibrated to arrive at a different set of parameters. For PM4SAND, G_0 is adopted from SANISAND-MS, and h_{p0} is calibrated by the PLAXIS Soil Test parameter optimization tool via SANISAND-MS predictions. The selected parameters are presented in Table 1.

Table 1. Parameters for Karlsruhe fine sand (KFS).

	SANI-04	SANI-MS	PM4-S	Tests
Elasticity				
G_0	150	95	90	DMT, UCT
ν	0.05	0.05	-	OED
Critical state				
M_c	1.34	1.35	-	UMT
c	0.7	0.81	-	UMT
λ_c	0.122	0.055	-	DMT, UMT, CS
e_c	1.103	1.035	-	OED, CS
ξ	0.205	0.36	-	DMT, UMT, CS
Yield surface				
m	0.05	0.01	-	-
Kinematic hardening				
h_0	10.5	7.6	-	DMT, UCT
c_h	0.75	0.97	-	DMT
n^b	1.2	1.2	-	DMT
Dilatancy				
A_0	0.9	0.74	-	DMT
n^d	2.0	1.79	-	DMT
Fabric dilatancy				
z_{max}	20	-	-	UCT
c_z	10000	-	-	UCT
Memory surface				
μ_0	-	82	-	UCT
ζ	-	0.0005	-	UCT
β	-	4	-	UCT
Contraction				
h_{po}	-	-	0.4	CPT, SPT

OED oedometric test, DMT drained monotonic triaxial test, UMT undrained monotonic triaxial test, UCT undrained cyclic triaxial test, SPT standard penetration test, CPT cone penetration test.

3 RESULTS AND DISCUSSION

OpenSees simulations are compared against the soil tests simulated by the commercial software PLAXIS, which uses a single-point algorithm. In this section, each model will be examined separately.

3.1 SANISAND04

While the model can predict the butterfly-shaped last cycles, it shows inadequate performance in realistically capturing the excess pore pressure development rate and the subsequent pace of effective stress reduction (Figure 1). Although the strain expands to both sides in the triaxial experiment, it accumulates more on the extension side. However, the prediction shows a stronger accumulation on the tension side with a pace different than the actual soil test data (Figure 2).

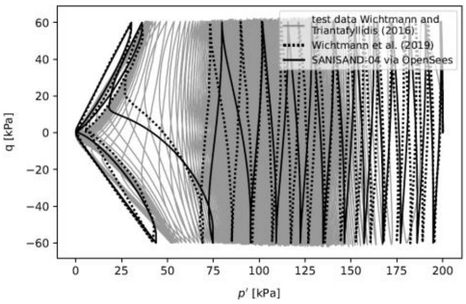


Figure 1. UCT results for q_{amp}=60 kPa, p_0=200 kPa, and D_{r0}=87%: deviatoric stress vs. effective mean pressure.

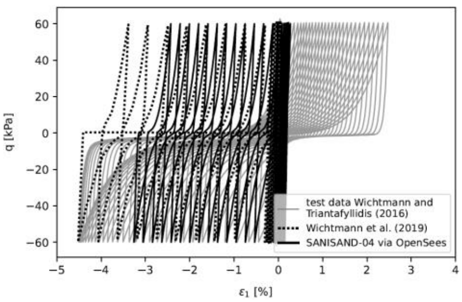
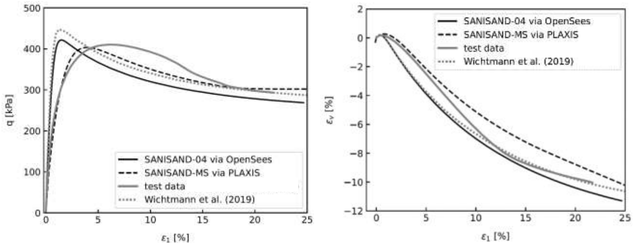


Figure 2. UCT results for q_{amp}=60 kPa, p_0=200 kPa, and D_{r0}=87%: deviatoric stress vs. axial strain.

3.2 SANISAND-MS

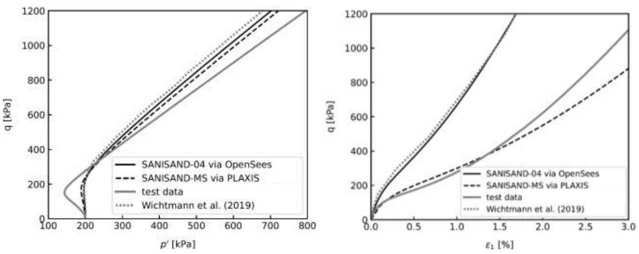
The model has been compared against SANISAND-04 since PM4SAND is formulated in plane strain conditions. For the drained analysis (Figure 3), SANISAND-MS appears to represent the triaxial test data more accurately than SANISAND-04, as it exhibits a trend that aligns more closely with the test results. Since both model parameters are calibrated towards cyclic loading tests, and it is known that one set of parameters for both cyclic and monotonic loading tests are not attainable, such results were anticipated.



(a) (b)

Figure 3. DMT results for p_0=100 kPa and D_{r0}=85%: (a) deviatoric stress vs. axial strain and (b) volumetric strain vs. axial strain.

For the undrained analysis (Figure 4), SANISAND-MS shows slightly better (but still higher in terms of stress ratio q/p) predictions considering the larger displacements it can predict under deviatoric stress. However, in terms of stress paths, none of the models could predict the dense-sand dilatant behavior as we expect from the triaxial tests. This proves the previous findings stating that the bounding surface cannot be adequately characterized solely by the mean effective stress and void ratio for all stress-strain paths.



(a) (b)

Figure 4. UMT results for p_0=200 kPa and D_{r0}=87%: (a) deviatoric stress vs. effective mean pressure and (b) deviatoric stress vs. axial strain.

Since a stress-controlled test was not possible for PLAXIS simulations, comparisons are held for a strain-controlled test. The differences are evident in the cyclic tests shown as can be seen in Figure 5 and Figure 6. The model predictions are similar yet deviate from the triaxial test data.

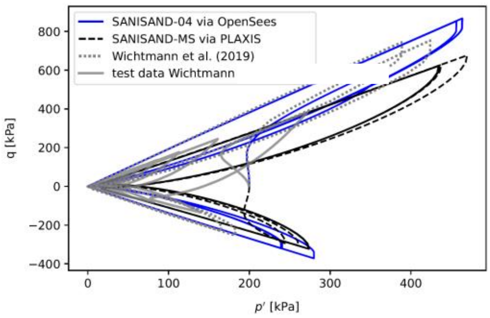


Figure 5. UCT results for ε_{amp}=1%, p0=200 kPa, and D_{r0}=94%: deviatoric stress vs. effective mean pressure.

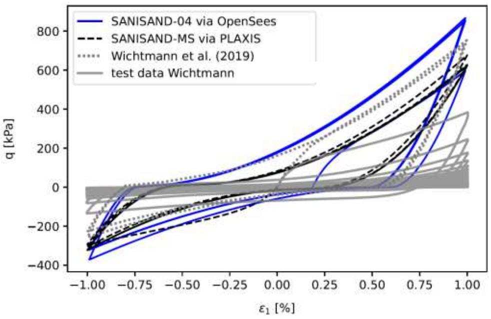


Figure 6. UCT results for ε_{amp}=1%, p_0=200 kPa, and D_{r0}=94%: deviatoric stress vs. axial strain.

3.3 PM4SAND

Figure 7 shows that SANISAND-04 and MS models exhibit similar stiffness degradation and damping with shear strain (with a higher dissipated energy for SANISAND-MS). PM4SAND predicts different behavior than these two models mostly attributed to parameter selection. This underscores the importance of secondary parameter calibration for the model.

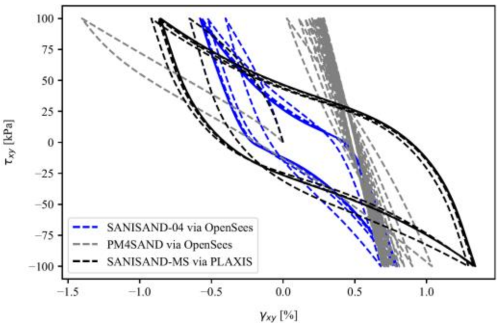


Figure 7. CDSS results for p_0=200 kPa and D_{r0}=94%: shear strain vs. shear stress.

4 CONCLUSIONS

This study aims to conduct a comparative analysis of two state-of-the-art constitutive models for sandy soils: SANISAND-MS and PM4SAND, with their predecessor SANISAND-04. The main findings of this work can be summarized as follows:

Despite the fact that the models can predict the butterfly-shaped loading path, the excess pore pressure development rate is not realistic.

Models are not that accurate in reproducing the strain development pace. This is more pronounced in high cyclic loading.

Since the models are engineered to accommodate certain conditions, when subjected to more complex loading scenarios, the models could yield results that are not in agreement with physical observations. As such, overshooting following immediate reloading or reverse loading can be attributed to the physics imposed within the mathematical formulations of the models.

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".

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