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Validation of REDWIN model in sandy soil under various drainage conditions

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ABSTRACT: Monopile foundations are the most common substructure type of offshore wind turbines (OWTs). The cost optimization in OWTs design requires the accurate and convenient modelling tools for offshore foundations. For this purpose, a macro-element model, the REDWIN monopile model, has been proposed. The REDWIN model has been proven to be a practical model to reveal the key fea-tures of soil-monopile-structure interaction in OWTs operation, in the integrated dynamic nonlinear time domain analyses in clay dominated soil profile. The REDWIN model is desired to be able to handle different types of soil conditions. In view of this, the validation of the REDWIN model in sandy soil has been presented in this work. The model is validated against 3D Finite Element (FE) analysis results under different loading history and soil drainage conditions. The comparison between the REDWIN model simulation results and 3D FE results proves the accuracy of REDWIN model performance in sand-dominated soil profile. Combing the simulation evidence from this work and the pioneer work in clay-dominated soil profile, the REDWIN model is believed to be a reliable modelling tool for complicated/layered soil domain.

Keywords: macro-element model, offshore monopile, sand, cyclic loading.

1 INTRODUCTION

The offshore wind energy is gaining increasing popularity to fight against greenhouse gas emissions (Ramirez et al., 2020). During the past years, offshore wind farms are moving towards deeper waters to gain rapid increasing in offshore wind capacity. Thus, the costs for offshore foundation fabrication and installation increased significantly. Among all foundation types for OWTs, monopiles are currently dominating the substructure type. The optimization of monopile design procedures is one of the objectives to contribute the reduction of the investment on offshore wind farms. Thus, there is a demand to understand and/or reproduce practical soil-monopile-structure interaction issues that can practically clarify the governing geotechnical issues including, but not limited to, foundation stiffness, damping, soil drainage and degradation in long term loading history. Significant numerical modelling researches have been carried out to study the response of monopile-supported OWTs, including:

(1). One dimensional (1D) p-y modelling methods. In this category, the interaction between monopile and surrounding soil is modelled via the compliant soil springs for the dedicated 1D behavior. The applicability of this method to predict pile behavior is questionable when, for instance, considering fundamental frequencies (Page et al., 2018). The very recent example belongs to this category is the PISA project (Byrne et al., 2019). However, the cyclic loading conditions are still out of picture of the PISA framework.

(2). Three-dimensional (3D) FE analysis of soil-foundation system using 'explicit' constitutive laws (Jostad et al., 2014). The term 'explicit' indicates that the model explicitly links soil/pile behaviour to the number of regular loading cycles. In this method, empirical strain (or pore water pressure) accumulation laws are applied into the soil domain to calculate monopile deformations. Extensive laboratory work is required to de-rive/verify the implemented empirical laws.

(3). Three-dimensional (3D) FE analysis of soil-foundation system using 'implicit' constitutive laws (Liu et al., 2019). Cyclic soil response is calculated as a sequence of stress/strain increments. This method is believed to have the highest protentional to reveal the governing geo-mechanisms in OWTs soil-structure interaction problems. However, due to the computational limitations, as well as the lack of accurate constitutive laws, this method is more commonly used in academic purpose (Jostad et al., 2020).

Apart from the methods listed above, numerical models based on '0D' approach is believed to be able to reproduce soil-monopile-structure interaction effects especially in dynamic integrated analysis of OWTs (Page et al., 2018). The models developed within this cate-gory, known as 'macro-element models', lump the soil-foundation into a representa-tive point. The foundation (and surrounding soil) response is simplified as the general load-displacement relationship of the representative point located at the interface separating the foundation system and the superstructure. Macro-element models are recognized as numerical efficient and allow for the convenient implementation in the engineering practice and design.

REDWIN (REDucing cost in offshore WINd) macro-element model for monopiles has been developed for accurate consideration of foundation stiffness and damping in integrated time-domain analysis (Page et al., 2018). The REDWIN model has been validated against 3D FE analysis results and field test results in cohesive soil domain. The model is capable of reproducing foundation responses including non-linear generalized load-displacement behavior and hysteretic response. However, the model capability in simulating pile response in sandy soil domain has not been discussed. In this paper, REDWIN model performance in sandy soil is discussed. The vali-dation is accomplished against the 3D FE simulation results under varying drainage conditions. The accurate predictions of the REDWIN model on monopile foundation response in both clay-dominated (Page et al., 2018) and sand-dominated soil profile give confidence in expanding the use of the model in general soil domain.

2 REDWIN PILE MODEL

The theoretical framework of the REDWIN model is shortly introduced in this section. Detailed explanations to the model formulations refer to (Page et al., 2018).

The REDWIN pile model is developed within the framework of multi-surface plasticity (Mrôz, 1967). The model is capable of accurately reproduce the nonlinear load-displacement response of the monopile foundation system. In detail, the model is efficient to describe the monopile response under coupled multi-directional loading condition. It can also properly estimate the nonlinear stiffness reduction of the foundation system at relatively high loading levels. The entire foundation system (soil-monopile) response is describe by the 6 Degree of Freedoms (DOFs), including 3 translational and 3 rotational DOFs. The model is recognized as accurate when comparing with 3D FE analysis results, with a significant reduction of computational costs (the computational time for REDWIN model can be as short as 1/1000 of that the 3D FE analysis costs).

REDWIN model loci are defined as the constant plastic work contours. The loci in M-H (moment – horizontal force at the seabed level) plane can be approximated as ellipses (as indicated in Figure 1) based on the 3D FE analysis results. The model describes the generalised load-displacement (or displacement increment, dv) behaviour based on the conventional elasto-plastic theory, which indicates that dv can be computed as the sum of the elastic contribution $\mathbf{dv}^{\mathrm{e}}$ and the plastic contribution $\mathbf{dv}^{\mathrm{p}}$. The elastic/elasto-plastic behaviour of the foundation is distinguished by the initial yield surface (as illustrated in Figure 1). The elastic load-displacement response (in incremental form) is defined in the elastic region. The generalised load increment dt is linked to the generalised elastic displacement $\mathbf{dv}^{\mathrm{e}}$ through the elastic stiffness matrix K. Pile geometries and properties effects, soil properties and drainage effects are all integrated into $\mathbf{K}$. The failure surface bounds all admissible force states. Other surfaces (loci) between the initial yield surface and the failure surface are named as loading surfaces. Due to the definition of constant plastic work for each yield surface, associated flow rule is derived for the REDWIN model. Thus, the direction of plastic displacement increment $\mathbf{dv}^{\mathrm{p}}$ is perpendicular to the contours of plastic work. According to Koiter's rule (Koiter, 1953), the $\mathbf{dv}^{\mathrm{p}}$ is determined by the sum of the plastic contributions of each activated loading surface.

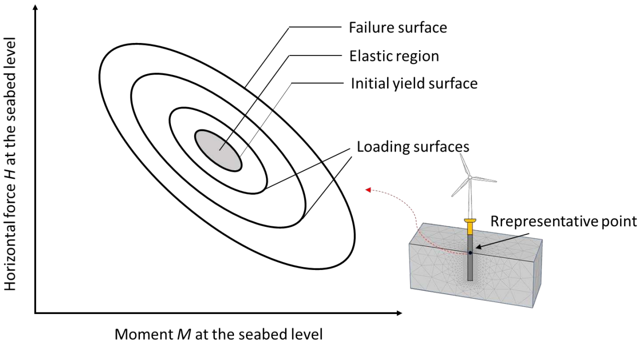


Figure 1. Lumped macro-element model and model surfaces.

The kinematic hardening law is adopted in REDWIN model. In elasto-plastic stage, the initial yield surface moves along plastic flow direction until the next loading surface is activated – after which the activated loading surface(s) move together with the initial yield surface. This procedure is guaranteed by applying consistency condition to each yield/loading surface. The evolution of the i^th^ yield/loading surface center $\mathbf{d\alpha}_{\mathrm{i}}$ is related to the plastic displacement increment $\mathbf{dv}^{\mathrm{p}}$ through the plastic stiffness matrix $\mathbf{K}_{\mathrm{i}}^{\mathrm{p}}$ for the ith surface. For each surface, $\mathbf{K}_{\mathrm{i}}^{\mathrm{p}}$ is assumed constant, which results in a piece-wise linear force-displacement curve.

3 REDWIN MODEL CALIBRATION

Calibration of REDWIN model requires two inputs:

(1) coefficients of the elastic stiffness matrix. This can be obtained from semi-empirical relationships (for example, provided by Gazetas (1991) if the soil profile is homogeneous). For layered soil domain, FE analysis results can be used for the calibration of the elastic stiffness matrix.

(2) static non-linear push-over load-displacement curve. Such an input can obtain from the FE analysis or directly from laboratory/in-situ tests. Two kinds of load-displacement relationships are required: moment M –

pile head displacement U_M (or pile head rotation θ_M) and horizontal force H-pile head displacement U_H (or pile head rotation θ_H) relationships.

Calibration of REDWIN model is soil profile specific and drainage condition specific – which means that if the soil profile has been changed or the drainage condition has been changed, the model need to be re-calibrated. Calibration of the REDWIN model is simple, flexible and has a direct physical interpretation. The accuracy of the REDWIN model depends highly on the load-displacement input. Detailed calibration procedures were identified in (Page et al., 2018). In this work, 3D FE analysis results are used for the calibration purposes. FE platform PLAXIS is adopted. Notice that to obtain inputs for REDWIN model, the monotonic monotonic horizontal load H and moment M are applied seperately. After this, the calibrated model inputs can be used for calculations of the same soil profile and the same drainage condition but different loading conditions (not only monotonic H nor only monotonic M, but also combined H and M, regular cyclic and irregular cyclic). The 3D FE model is illustrated in Figure 2. SANISAND model (Dafalias and Manzari, 2004) is used for the soil behaviour simulation. Detailed model parameters will not be given for brevity. The pile geometry and properties are summarized in Table 1. The monopile is simulated as soil pile but has the same stiffness as a tubular pile with a wall thickness t=0.1m. The Young's modulus for the equivalent solid pile is therefore calculated as 20.56 GPa.

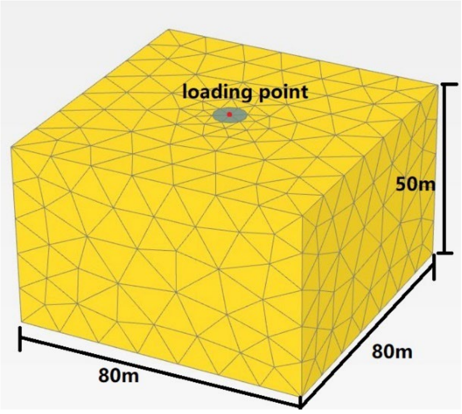


Figure 2. 3D FE model of laterally loaded monopile.

Table 1. pile geometry and material properties adopted in the 3D FE analyses

Embedded length L [m]	22.5
Diameter D [m]	9
Thickness t [m]	0.1
Young's modulus [GPa]	20.56
Steel Poisson ratio	0.3

The two input curves are obtained from the two push-over analyses: (1) only horizontal load H = 50 MN is applied at the loading point (located at the seabed level, see Figure 2); (2) only moment M = 800 MNm is applied at the loading point.

For push-over analysis, three sets of FE simulations are performed under drained, partially drained and undrained conditions. The outcome load-displacement relation-ships are obtained and be used as the inputs for REDWIN model simulation under different drainage conditions. For partially drained calibration, the permeability of the sand is set as 5.0e-6 m/s; the loads are applied with a duration of 69s for H and 9s for M – such durations are derived from the 1-hour WAS-XL wind speed bin (Jostad et al., 2020). The calibrated REDWIN load-displacement curves are compared with the SANISAND 3D FE analysis results in Figure 3.

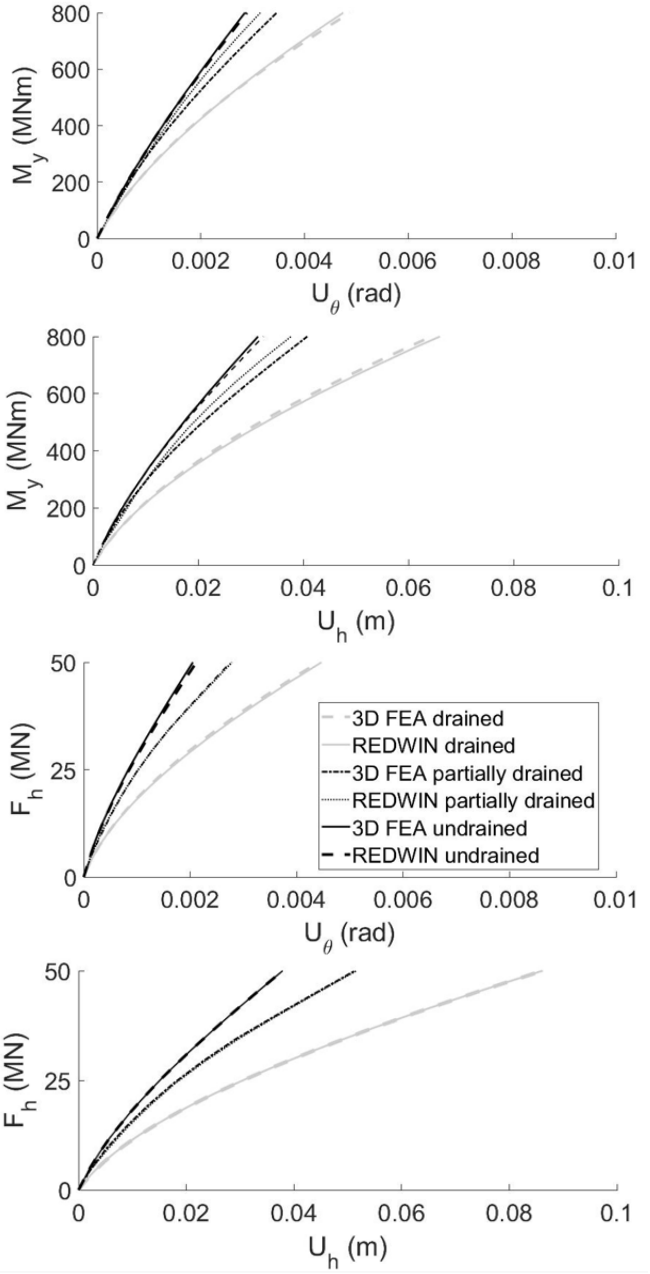


Figure 3. Calibration of REDWIN model through 3D FE results using SANISAND model

Very good matches are observed for all cases. The cali-brated REDWIN load-displacement curves are considered as adequate to reproduce the pile push-over responses and efficient to consider impact from pile geometry, soil properties and drainage conditions obtained from 3D FEA, during the model calibra-tion process.

4 REDWIN MODEL PERFORMANCE UNDER CYCLIC LOADING CONDITIONS

In this section, REDWIN model performance in sand domain are investigated under cyclic loading conditions. In what follows, the loading rate, soil drainage conditions are the same as in the corresponding calibration process. SANISAND 3D FE model simulation results are used for comparison. The simulations are performed with the same FE model as illustrated in Figure 2. Notice that the calibration procedure is finished through push-over analysis. However, the simulations presented in this section are under cyclic loading conditions.

4.1 REDWIN model performance under symmetric sinusoidal loading

Though environmental loading in nature is irregular and multidirectional, the perfor-mance of REDWIN model in reproducing pile behavior under symmetric sinusoidal loading condition is investigated first due to the wide awareness based on extensive tests/simulations in literatures. The behavior of the REDWIN model is compared with the SANISAND 3D FE simulation results in Figure 4. Only the partially drained condition is studied for brevity. Symmetric sinusoidal moment M is applied at the pile head.

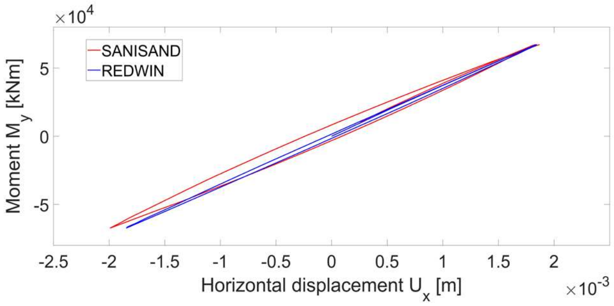
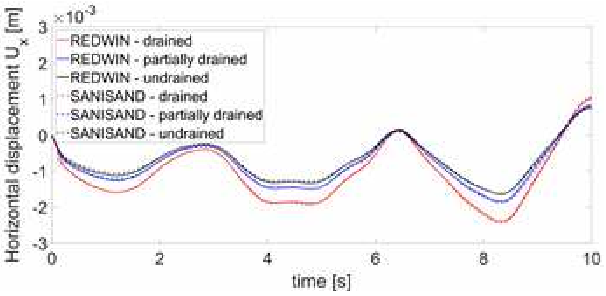


Figure 4. Validation of REDWIN model against sinusoidal loading cycle (bending moment M) under partially drained condition.

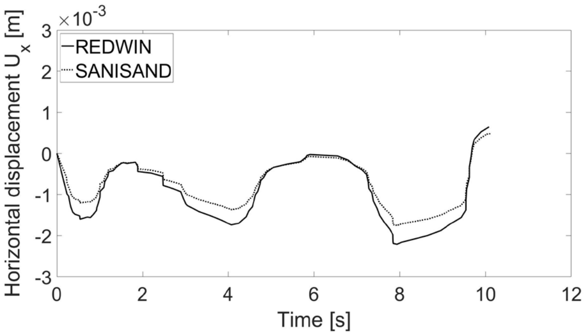
The comparison result suggests during the initial loading procedure, REDWIN sim-ulation result is nearly identical with SANISAND 3D FE analysis results. Upon un-loading and reloading, REDWIN model predicts slight stiffer foundation response – which can be neglected. Another difference is that REDWIN model predicts close-end load-displacement loop, while there is slight displacement accumulation predict-ed by SANISAND 3D FE model. This is due to the formulating purpose of REDWIN model -- the main application of the REDWIN model is to account for the model fatigue behavior under relatively small load levels and short durations, where no sig-nificant pile displacement is accumulated (see for instance, Page et al., 2018 for details). Bearing this in mind, the performance of the REDWIN model under such simplified simulation conditions is considered accurate, as suggested by Figure 4.

4.2 REDWIN model performance under irregular loading history

To further validate the model against irregular loading results, a 10s WAS-XL loading history is adopted. Figure 5**(a)** compares the REDWIN simulation results with SANISAND 3D FE simulation results. The simulations were performed under drained, partially drained and undrained conditions. Only bending moment M was applied at pile head. For all cases, REDWIN simulation results agree well with SANISAND 3D FE results. It suggests that REDWIN is reliable in reproducing foundation response under the real-life loading conditions. Drainage effects can be well captured through the calibration procedure.



(a) M only



(b) Combined H and M

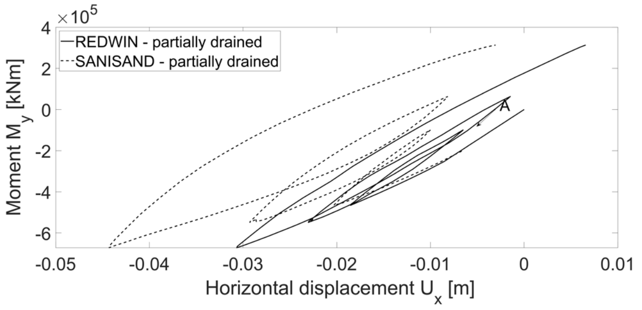
Figure 5. Pile response subjected to10s WAS-XL loading: (a) bending moment M only, simulations performed under drained, partially drained and undrained conditions; (b) combined horizontal load H and bending moment M, under partially drained condition.

Such a conclusion is further enhanced by comparing REDWIN model simulation result with SANISAND 3D FEA result under partially drained condition but subjected to combined horizontal load H and moment M – as presented in Figure 5**(b)**. Satisfactory match between the two simulation results is obtained.

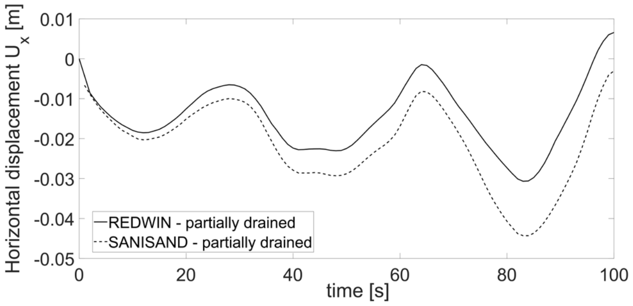
5 DISCUSSION

Though REDWIN model is not meant for studying foundation response under very large loading conditions, it is worth to show such kind of evidence for reasonable use of the model. The partially drained case is selected for clarification. In detail, the adopted 10s WAS-XL is scaled up with a factor of 10, for both the load level and the duration (so that the loading rate keeps the same).

REDWIN model simulation results are compared with the SANISAND 3D FE model in Figure 6(a). Starting from point A, relatively good agreement has been captured at relatively low M level (up to 2e5 kNm). After that, the REDWIN model result starts to diverge from the SANISAND 3D FE result. In general, the REDWIN model reproduce much stiffer foundation behaviour compared to that predicted by SANISAND 3D FE model (Figure 6). Such disagreement is in line with the observations from Figure 4 and can be observed both from monopile load-displacement response and time-domain displacement evolution response. With no intention to argue which simulation result is more accurate, here the purpose of this comparison is to emphasize the importance of employing the REDWIN model within the scope of definition (i.e., relatively small loading condition).



(a) Moment against pile head displacement



(b) Pile head displacement against time

Figure 6. Pile response subjected to10s WAS-XL loading (with bending moment scaled up to 10 times), under partially drained condition.

6 CONCLUSION

The performance of REDWIN model in sand domain has been investigated in this paper. Model calibrations are finished under drained, partially drained and undrained conditions based on the SANISAND 3D FE simulation result. REDWIN model is calibrated against 3D FE analysis of monotoniccally loaded monopile under the conditions of only horizontal load H and only moment M under the predefied drainage conditions. However, the calibrated REDWIN model inputs can be used into other loading conditions such as combined H and M, regular cyclic loading, irregular cyclic loading under the condition of the same soil profile and the same drainage.

Both regular and irregular (10s WAS-XL) loading history are applied to the predefined monopile foundation system. Under the desired loading range, REDWIN model predicts accurate foundation response when compared with the corresponding SANISAND 3D FE simulation results. The comparison results support the use of REDWIN model in sand-dominated soil profile and, to a step further, in layered soil profiles due to the already established suitability in clay-dominated soil profile. For load levels beyond the fatigue analysis limit, the use of REDWIN model needs detailed evaluation.

7 ACKNOWLEDGEMENTS

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