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Prediction of short piles response to lateral monotonic load in dense sand at Blessington

Prédictions de la réponse de pieux courts sous charge monotonique latérale dans le sable dense de Blessington

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ABSTRACT: This paper presents some initial results of an experimental campaign aimed at extending the existing database of pile lateral field tests. Monopiles with low slenderness ratios (L/D, ratio of pile embedment to pile diameter) less than 4.5 are deemed to be representative of current and future monopile foundation designs for the offshore wind industry. The monopile field testing consisted of both monotonic and cyclic tests with slenderness ranging from 2.2 to 4.4. A total of 6 piles with an outer diameter of 457 mm were driven and tested in dense sand at the Blessington test site, located south to Dublin in Ireland. Three different approaches were used to predict the monotonic pile responses. Traditional approaches (API and PISA rule) were found to significantly underestimate both piles stiffness and ultimate capacity. A novel set of CPT based correlations of HS-small parameters for three-dimensional finite-element analyses recently developed by Trinity College Dublin was found to provide very accurate predictions of both stiffness and ultimate reaction.

RÉSUMÉ: Cet article présente les premiers résultats d'une campagne expérimentale visant à étendre la base de données existante d'essais in-situ de pieux chargés latéralement. Des rapports d'élancement (L/D, rapport entre la profondeur et le diamètre du pieu) plus faibles sont plus représentatifs des dimensions des fondations monopieux supportant actuellement les éoliennes en mer. Des pieux avec des rapports d'élancement allant de 2.2 à 4.4 ont été testés sous charges monotoniques et cycliques. Au total, 6 pieux d'un diamètre extérieur de 457 mm ont été battues et testés dans du sable dense sur le site d'essai de Blessington, situé au sud de Dublin en Irlande. Trois approches différentes ont été utilisées pour prédire la réponse des pieux sous chargement monotone. Les approches traditionnelles (API et PISA rule) ont sous-estimé de manière significative la rigidité et la capacité ultime des pieux. Trinity College Dublin a récemment développé un jeu de corrélations basées sur le CPT pour les paramètres du model de sol constitutif HS-small, populaire pour les analyses éléments finis 3D. Cette approche s'est avérée fournir des prédictions très précises de la rigidité et de la réaction ultime des pieux.

Keywords: Offshore wind; geotechnical engineering; monopiles; field tests.

1 INTRODUCTION

This paper outlines the preliminary findings from an experimental initiative aimed at expanding the current repository of lateral field tests for low L/D monopiles. Monopiles are large diameter open ended steel pipe piles which are typically impact driven into the seabed and are the most commonly used foundation for offshore wind turbines. As the offshore wind industry matures, larger wind turbines are being designed which require monopiles with diameters in excess of 10 m. These XL monopiles typically have slenderness ratios (L/D, where L is the embedded length and D the diameter) less than 4.5. In this paper, the results from one of the monotonic field test piles with L/D=3.3 is compared to three different approaches for predicting the lateral responses of the piles. The paper shows that current rule-based beam-spring approaches such as API (2011) and PISA-rule based method (Burd et al. 2020) both significantly underestimate the stiffness and ultimate capacity of these small scale piles. In contrast, a 3D Finite Element approach developed at Trinity College Dublin, using CPT-based correlations, provides highly accurate predictions for the entire load-displacement response.

2 METHODOLOGIES

This section presents 3 different approaches to predict the response of piles subjected to monotonic lateral loading in sands.

2.1 API

The traditional industry practice used to follow the oil and gas industry design standard (API, 2014). The 'p-y approach' involves modelling the pile by means of one-dimensional elastic beam elements. At each depth, a 'p-y curve' defines the non-linear relationship between the soil resistance, p, mobilised as a result of the pile lateral displacement, y. The soil layers are assumed to behave independently, therefore the curves are uncoupled. API RP 2GEO (API, 2014) provides basis for the formulation of the non-linear p-y curves in sands, soft clays and stiff clays. In sands, it takes the form of a hyperbolic tangent as shown by equation (1):

$$p = Ap_u \tanh\left(\frac{kz}{Ap_u}y\right) \tag{1}$$

where:

- $A = \left(3 - 0.8\frac{z}{D}\right) \geq 0.9$ for monotonic loading.
- p_u is the ultimate lateral resistance at depth z.
- k is the rate of increase with depth of initial modulus of subgrade reaction at depth z.
- y is the lateral pile deflection at depth z.
- z is the depth below ground level.

The interested reader is invited to refer to API (2014) section 8.5.6 for additional information, including basis for calculation of p_u and k.

2.2 PISA rule

The PISA design model (Burd et al., 2020) represents the state-of-the-art design methodology for monopiles and is now used globally in the industry. Like API, the PISA approach rely on one-dimensional finite-element analyses. However, PISA considers three other soil reaction components in addition to the distributed lateral load: the distributed moment, the base shear and the base moment (see Figure 1). The soil reaction curves can be constructed from a set of equations referred to as 'depth variation functions' (DVFs). The DVFs provide basis to generate nornalised soil reaction curves. The soil inputs required to un-normalised the curves in sand are the soil realtive density, small strain shear modulus, and unit weight. Following the PISA rule-based approach, the DVFs from the Generalised Dunkirk Sand Model (GDSM) developed by Burd et al. (2020) is considered in this study.

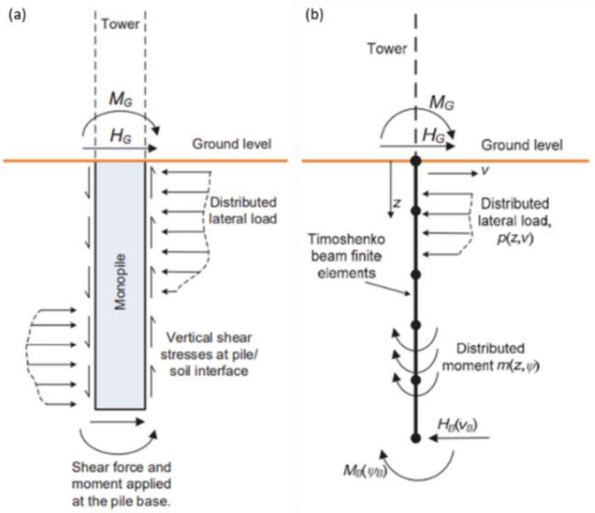

Figure 1. PISA design model: (a) soil reaction components acting on the pile; (b) implementation in 1D FE (after Burd et al., 2019).

2.3 3D FEA

With the development of computational power, it is now standard practice to use three-dimensional finite element analyses for monopile design.

In this study, the piles were modelled at full scale and half-space in Plaxis 3D. The pile structure is modelled using linear-elastic isotropic plate elements with standard steel properties (Young's modulus of 210 GPa and Poisson's ratio of 0.3). The pile is weightless since the focus is on lateral loading. Interfaces at the outside and inside of the pile capture the soil-structure interactions.

The sand is modelled with the Hardening soil model with small strain stiffness (HS-small) assuming drained conditions. All the inputs required for the constitutive models were calibrated from site specific CPTs following the approach recently developed in Trinity College Dublin and presented in Igoe and Jalilvand (2020). The approach has already been validated against a large database of lateral pile field tests, including the PISA test in Dunkirk.

3 EXPERIMENTAL CAMPAIGN

The test site is located in Blessington, in an active quarry approximately 25 km south-west of Dublin, Ireland. Prior to pile installation, cone penetration testing (CPT) was undertaken at each desired pile location. Relevant CPT profiles are plotted on Figure 2 demonstrating minimum vertical or lateral soil variability. The site comprises of homogenous dense sand deposits.

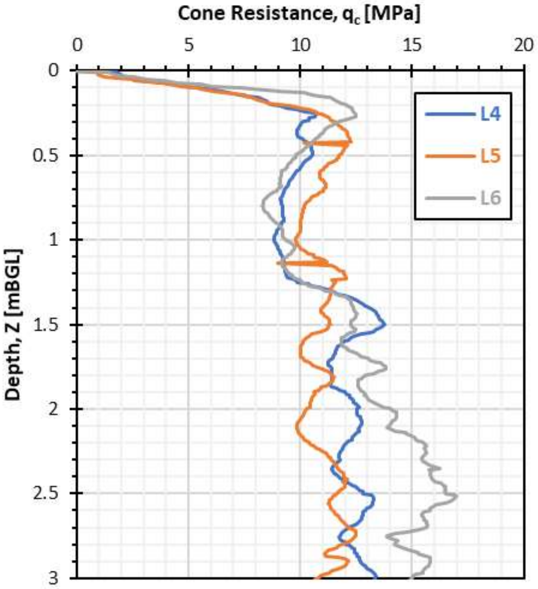

Figure 2. CPT profiles in terms of cone tip resistance (after Lapastoure and Igoe, 2024).

A total of 6 piles with an outer diameter (D) of 457 mm were driven at CPT locations. Pile embedded lengths (L) are ranging from 1 m to 2 m (L/D ranging from 2.2 to 4.4). The piles were installed in a 3x2 grid with the longer piles installed at the centre as shown on Figure 3. The longer piles were used as reaction piles to test the shorter piles. A stick-up length of 1.5 m was left out to ensure the lateral load could be applied with sufficient eccentricity to be representative of offshore conditions. The loads were applied at an eccentricity of 1.37 m (about 3*D).

During each test, both piles were instrumented with inclinometers and linear variable differential transducer at ground level. The lateral load was applied with a hydraulic jack and measured with a tension load cell. The experimental campaign consisted of 5 field tests:

- Test 1: Monotonic test between L6 (L/D=2.2) and L5 (L/D=4.4).
- Test 2: Monotonic test between L4 (L/D=3.3) and L5 (L/D=4.4).
- Test 3: Cyclic test (4000 cycles in total) followed by monotonic push over between L3 (L/D=3.3) and L2 (L/D=4.4).
- Test 4: Cyclic test (3670 cycles in total) followed by monotonic push over between L1 (L/D=2.2) and L2 (L/D=4.4).
- Test 5: Cyclic test (3160 cycles in total) between L2 (L/D=4.4) and L5 (L/D=4.4).

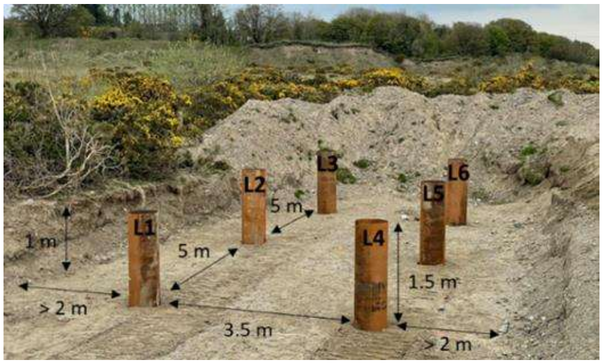

Figure 3. Piles arrangement (after Lapastoure and Igoe, 2024).

Only the results of the monotonic tests are considered for this study (Test 1 and Test 2). The interested reader is invited to refer to Lapastoure and Igoe (2024) for more information.

4 PRELIMINARY RESULTS

Figure 4 presents a comparison of experimental and predicted load-displacement response at ground level for pile L4 (L/D=3.3). For consistency, all three approaches (API, PISA rule and 3D FEA) are based on the soil parameters correlated from the CPT based approach presented in section 2.3 (all parameters provided in Igoe & Lapastoure, 2024). The predictions based on the API and PISA rule approaches are found much softer than the actual pile response. The 3D FEA approach is found to provide a very good prediction.

Figure 4 presents a comparison of experimental and predicted load-displacement response at ground level for pile L4 (L/D=3.3). For consistency, all three approaches (API, PISA rule and 3D FEA) are based on the soil parameters correlated from the CPT based approach presented in section 2.3 (all parameters provided in Igoe & Lapastoure, 2024). The predictions based on the API and PISA rule approaches are found much softer than the actual pile response. The 3D FEA approach is found to provide a very good prediction.

Table 1 compares the blind predicitons to the experimental response for piles L4 (L/D=3.3), L5 (L/D=4.4) and L6 (L/D=2.2) in terms of initial stiffness and ultimate reaction. The initial stiffness is defined as the secant stiffness for a pile displacement of D/1000 at ground level, where D is the pile diameter. The ultimate reaction is defined for a pile displacement of D/10 at ground level for the numerical models, and as the maximum lateral load reached for the experimental tests. Ultimate reaction could not be reached during the test for L5 due to limitations with the loading system.

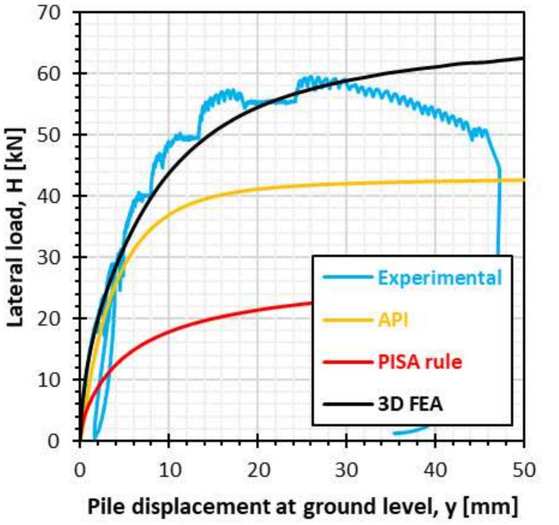

Figure 4. Comparison of experimental and predicted load-displacement response at ground level for pile L4 (L/D=3.3).

PISA rule is found to largely underestimate the stiffnesses and the ultimate reactions by more than 50%. This is because the depth variation functions from the General Dunkirk Sand Model (GDSM) are being used outside of their calibration space. Indeed, Burd et al. (2020) calibrated the GDSM against three-dimensional finite element analyses with pile diameters ranging from 5 m to 10 m. In this experimental study, piles have a diameter of 457 mm.

Although the API ‘p-y‘ approach was developed for long and flexible piles, it is found to perform slightly better than PISA rule for these short and rigid piles. However, it still significantly underestimates stiffnesses (37% to 53%) and ultimate reactions (about 30%).

3D FEA is found to provide very good matches with the experimental data, the average error being less than 5% accross the different pile penetrations. These results further validate the CPT based correlations of HS-small parameters developed by Igoe and Jalilvand (2020).

Table 1. Comparison of blind predictions to experimental piles response in terms of initial stiffness and ultimate capacity.

Approach	Initial stiffness relative error [%]			Ultimate capacity relative error [%]		
	L4	L5	L6	L4	L5	L6
Field test	Ref	Ref	Ref	Ref	-	Ref
API	-44.4	-36.9	-53.3	-28.6	-	-30.6
PISA rule	-50.9	-48.8	-57.9	-59.2	-	-57.3
3D FEA	8.8	4.5	5.6	3.9	-	-2

5 CONCLUSION

This paper presents the initial results of a recent campaign of pile lateral field tests. 6 piles with diameter of 457 mm and penetration ranging from 1 m to 2 m were driven into dense sands at the Blessington test site in Ireland and subjected to monotonic and cyclic loading.

The piles response to monotonic loading were predicted ahead of testing using three approaches: API ‘p-y curve’ approach, PISA rule-based approach and three-dimensional finite-element analysis with a novel set of CPT based correlations for all the input parameters to the soil constitutive model. The API and the PISA rule approaches were found to largely underestimate both initial stiffness and ultimate reaction for all piles. The 3D FEA prediction with CPT based input parameters were found to match very well with the experimental monotonic response for all piles.

These results further validate the CPT based correlations developed by Igoe and Jalilvand (2020) and suggest that the approach can be used for monopile foundations design supporting offshore wind turbines which are characterised by low slenderness ratios (L/D). The full list of correlations and parameters used in the 3D FE modelling is provided in Igoe and Lapastoure (2024).

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