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Insight into the cyclic response of OWT pile foundations in clay: Numerical simulation of PISA field tests

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ABSTRACT: The Ta-Ger elasto-plastic constitutive framework (Tasiopoulou and Gerolymos, 2016a,b), originally used to simulate sand-like responses under monotonic and cyclic loading was extended to capture clay-like responses (Tasiopoulou et al.,2024) including features such as shear modulus degradation with strain level and number of loading cycles, hysteretic damping, softening and ratcheting under asymmetric loading. The Ta-Ger model for clays was used for 3D simulation of selected field tests of monopiles in Cowden clay conducted as part of the PISA program. The test piles simulated were 0.762-m "medium" diameter piles subjected to both monotonic and cyclic lateral and overturning loading. Comparison between numerical results and test measurements show that the simulations can reproduce the basic mechanisms of the monopile/soil system response, under both monotonic and cyclic loading. Features reproduced in the simulations include the accumulation of lateral displacement and rotation due to one-way cyclic loading. It is shown that the numerical methodology can be used to gain insight into soil-OWT foundation interaction mechanisms and to derive the soil reactions acting on the foundations as a result of lateral and overturning loads.

Keywords: monopile, OWT, clay, PISA field tests, Ta-Ger model

1 INTRODUCTION

Monopiles represent about 80% of installed OWT foundations and their dimensions are usually controlled by cyclic loads. During the service lifetime of an OWT, the foundations are subjected to many loading cycles induced by wave and wind action. These types of loads can alter the mechanical properties and structure of the foundation soil and cause deformations of the foundation/structure system, such as rotation and lateral displacement, that can be critical to the performance of the OWT. Thus, the design of OWT foundations is mostly controlled by these types of cyclic loads.

The PISA project, including field testing and 3D finite element modelling, was planned and executed (Byrne et al., 2019a,b; Zdravković et al., 2020a,b; Burd et al., 2019a,b; Taborda et al., 2019 and McAdam et al., 2019) to provide data on the performance of monopiles under lateral loading, and to develop improved design approaches. The field testing involved lateral loading under monotonic and cyclic conditions applied to monopiles with L/D ratios varying between 3 and 10. Three characteristic pile diameters were chosen: i) small (D = 0.273 m), ii) medium (D = 0.762 m) and iii) large (D = 2 m). Tests were conducted at two onshore sites: an overconsolidated clay (Till) site at Cowden in the UK (Byrne et al., 2020a,b) and a dense/medium dense sand site at Dunkirk in France (McAdam et al., 2019).

This paper describes 3D numerical modeling conducted with FLAC 3D (Itasca, 2019) and the Ta-Ger constitutive model for clay (Tasiopoulou et al., 2024) to reproduce PISA field tests of selected medium-diameter monopiles in Cowden clay subjected to both monotonic and cyclic loading. The numerical methodology has been systematically validated against field and centrifuge test data on monopiles and suctions buckets founded on sand subjected to monotonic/cyclic lateral and overturning load (Tasiopoulou et al., 2020, 2021; Chaloulos et al., 2020, 2024). The objective of this study was to further validate the numerical methodology against field tests on monopiles founded on clayey soil conditions, in order to provide a holistically reliable and practical numerical tool that can used in the analyses and design optimization of OWT foundations for all types of soil conditions.

2 3D NUMERICAL MODELING OF PISA FIELD TESTS IN CLAY

2.1 Description of the simulated tests

Analyses were performed to simulate: i) monotonic tests CM2, CM3 and CM9 (Cowden Medium monopile with D=0.762m) and monopile length L=2.0, 4.0 and 7.6m and L/D ratios of 3.0, 5.25 and 10, respectively and ii) part of the cyclic test CM6 with the same L, D as the monopile in test CM9. For the monotonic analyses, the monopiles were subjected to a lateral load applied at a height of 10 m above the ground (Byrne et al., 2020a). For the cyclic analyses, the monopile was subjected to 37 one-way loading cycles with a maximum lateral load of 90 kN applied at a height of 10 m above the ground resulting in a maximum moment equal to 900 kNm. This cyclic load corresponds to the 3rd (and highest) load package in the cyclic loading sequence applied during the CM6 test.

The test site consists primarily of a heavily overconsolidated glacial clay (Zdravković et al, 2020a,b), and the water table is approximately 1m below the ground surface.

2.2 3D Mesh

The FLAC3D mesh used to model the tests is shown on Figure 1. The problem geometry is symmetric with respect to the vertical plane that passes through the centre of the monopile, thus only half of the geometry is analyzed. The discretization of the mesh, being radial in the horizontal plane, becomes denser towards the center of the model, close to the monopile. The monopile is simulated with isotropic elastic shell elements defined in terms of thickness, t_s = 10, 13, 14 and 11 mm for CM2, CM3, CM9 and CM6 respectively, density ρ_s = 8 g/cm^3 and Young's elastic modulus of steel, E_s = 200 GPa.

Interface elements were placed between the shell elements and the surrounding soil, described by Coulomb's friction law, with zero friction angle and cohesion equal to the idealized shear strength. The shear and normal interface stiffness parameters were assigned high values to assure that the stiffness is controlled by the soil elements.

Once the 3D mesh was developed, gravity was applied to obtain the initial geostatic stress field under K_0 conditions. The values of the coefficient of earth pressue at rest, K_0, varies from 1.5 at shallow depths to 0.94 at greater depth depending on the OCR distribution with depth. After gravity application, a lateral load was applied at the head of the monopile.

2.3 Constitutive model for Cowden clay

The Ta-Ger constitutive model for clays was used to simulate Cowden Till behavior. The basic formulation of the Ta-Ger constitutive framework is described in Tasiopoulou & Gerolymos (2016a,b) where it was applied to sands. The Ta-Ger constitutive models can be regarded as bounding surface models, within a smooth hysteresis framework, avoiding classical elasto-plasticity requirements for an initial elastic response, an explicitly defined plastic modulus and a loading index. The formulation provides a definite and continuous expression of an elasto-plastic matrix, rendering the numerical analyses computationally efficient. For example, one 600 s time history analysis of a 3D model like the ones presented in the report takes only about 2 days to complete with a conventional PC.

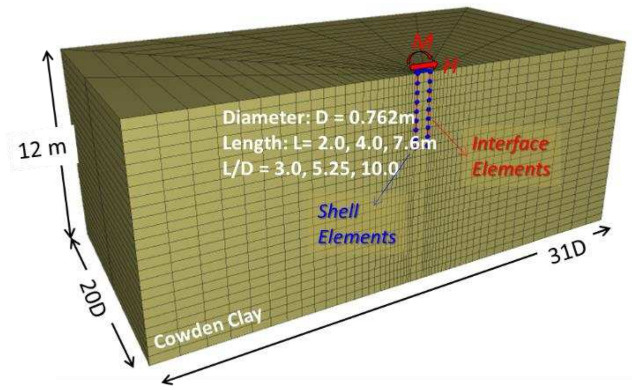

Figure 1. 3-D finite difference model and b) details of the monopile model.

The Ta-Ger elasto-plasticity framework is a simple, efficient, and versatile scheme operating in multiaxial space and it can be combined with an appropriate bounding surface and flow rule to model different soil behaviors. The framework has been used to develop constitutive models for sand and clay which have both been both implemented by GR8 GEO in FLAC (Itasca, 2016) and FLAC3D (Itasca, 2019). For sands, it operates in an effective stress regime using a stress-ratio dependent, open-ended bounding surface as a function of Lode angle together with an appropriate non-associative flow rule for cohesionless soils that develops volumetric strains under shearing through a phase transformation (i.e. dilatancy) surface. (Tasiopoulou and Gerolymos, 2016a,b; Tasiopoulou et al., 2020; Tasiopoulou et al., 2021). For clays, the Ta-Ger constitutive elasto-plastic framework operates in a total stress regime using a Von Mises type of bounding surface defined by the undrained shear strength, S_u, accounting for loading-path anisotropy through Lode angle, accompanied with an associative flow rule. The model formulation is described in Tasiopoulou et al. (2024). An example of Ta-Ger clay model prediction against a 2-way cyclic direct simple shear (CSS) test on a clayey sample under constant stress amplitude is given in Figure 2 in terms of shear stress-strain loops.

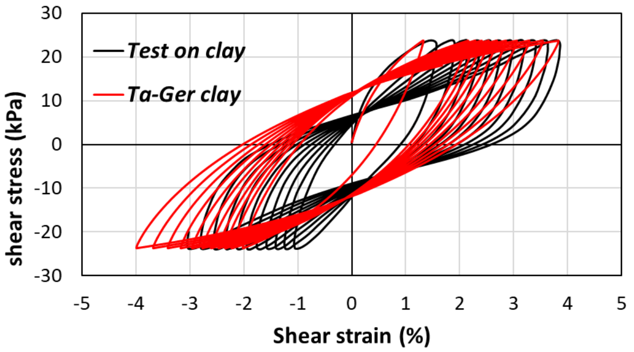

Figure 2. An example of Ta-Ger clay model prediction against a 2-way CSS test on a clayey sample under constant stress amplitude.

Figure 3 presents in situ and laboratory measurements of undrained shear strength S_u, and initial (small-strain) stiffness G_{max} together with idealized profiles from Byrne et al. (2020b). The idealized parameters used for the Ta-Ger clay model calibration in this study are shown with magenta colour. For the Ta-Ger clay model calibration, three clayey units were identified with different shear wave velocity, V_s, over undrained shear strength, S_u, ratios: i) "top" (magenta), ii) middle ("mid"-green) and iii) bottom ("bot"-orange) units, as depicted in Figure 4. The Ta-Ger clay model parameters were calibrated for each unit against stiffness degradation (G/G_{max}) and damping ratio versus strain based on laboratory tests on Cowden clay (Zdravković et al., 2020a; Ushev, 2017), as illustrated on the plots of Figure 4. The damping ratio predicted by the calibrated model is on the lower range of the available data which is a conservative approach for estimating system response. The values of the calibrated Ta-Ger clay model paramteres are shown on Table 1.

Table 1. Calibration of Ta-Ger clay hardening model parameters

Ta-Ger clay model parameters	Values
$n_{0,1}$	1.5
$n_{0,2}$	1
$n_{\zeta,1}$	0.2
$n_{\zeta,2}$	0.5
γ_{ref}	0.05
$n_{f,1}$	0.1
$n_{f,2}$	0
c	0

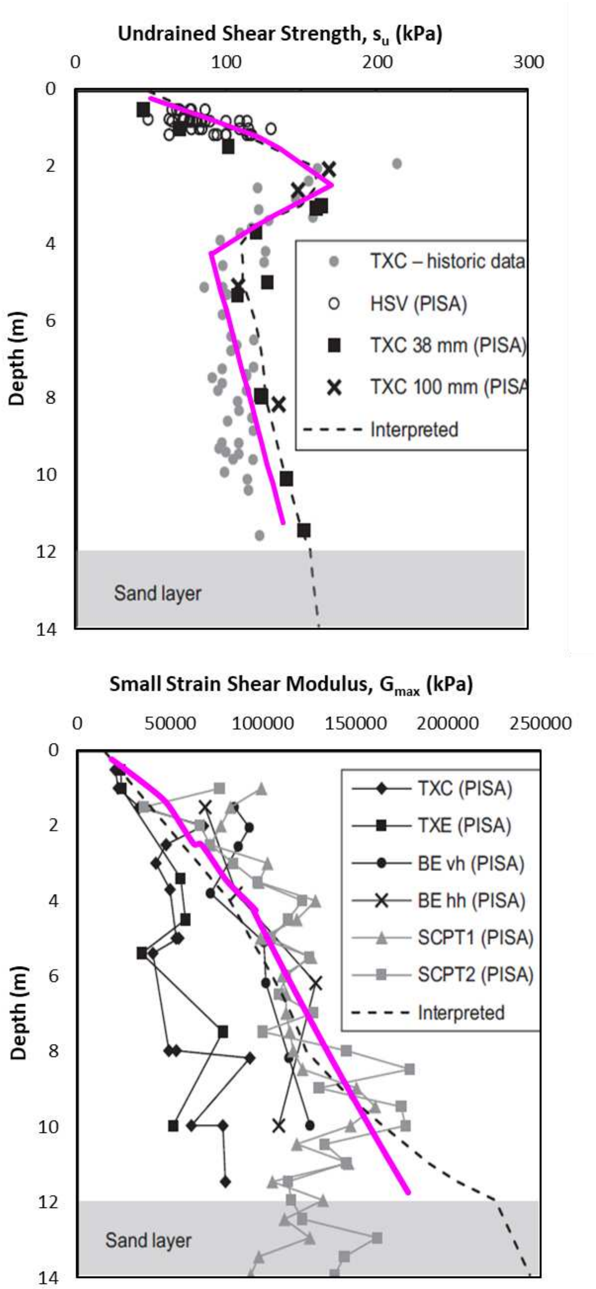

Figure 3. Strength (top) and stiffness (bottom) characteristics of Cowden Till.

3 NUMERICAL VALIDATION AGAINST FIELD TEST MEASUREMENTS

3.1 Monotonic Loading

The deformation of the CM9 (L/D=5.25) monopile under monotonic loading is shown on Figure 5 together with contour plots of horizontal displacement. As shown on that figure, the applied loads result in near rigid-body rotation of the monopile about a mid-depth pole of rotation with lateral displacement of the upper part of the monopile in the direction of loading, and the tip of the monopile kicking back. An approximately 1.5-2m deep gap was created at the interface between soil and monopile for all cases analyzed, compared to 1.65-, 2.2-, and 3.66-m gaps measured in field tests CM2, CM9 and CM3, respectively (Byrne et al. 2020b). The numerical methodology adopted resonably reproduces the gap formation between the soil and the pile, which may have a significant influence on the pile response.

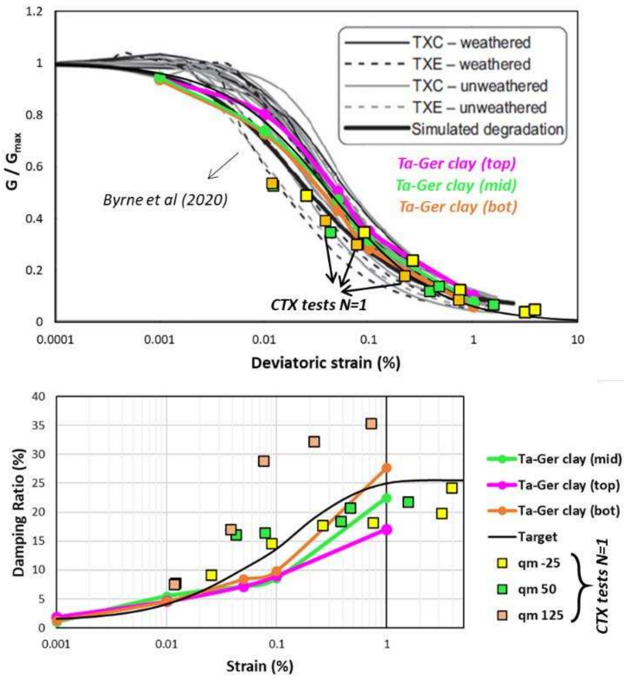

Figure 4. Stiffness degradation and damping ratio versus strain obtained by simulations with calibrated Ta-Ger model for clay versus laboratory data (Zdravković et al., 2020a; Ushev, 2017).

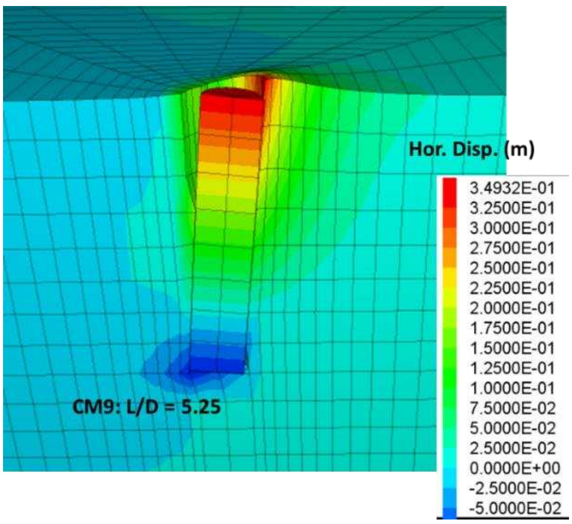

Figure 5. Deformed mesh for test CM9.

Comparison between numerical results and test measurements in terms of lateral force-displacement curves (Byrne et al., 2020b; Zdravkovic et al.., 2020a) for the monotonic tests are shown on Figure 6 for monopiles CM2 (L/D=3.0), CM9 (L/D=5.25), and CM3 (L/D=10.0) respectively. Numerical results are shown in magenta and experimental measurements in black. Also plotted on the figures (black dashed lines) are the numerical predictions by Zdravkovic et al (2020b). As shown on the figure the numerical analysis reasonably reproduced both the nonlinear response and the capacity of the foundation.

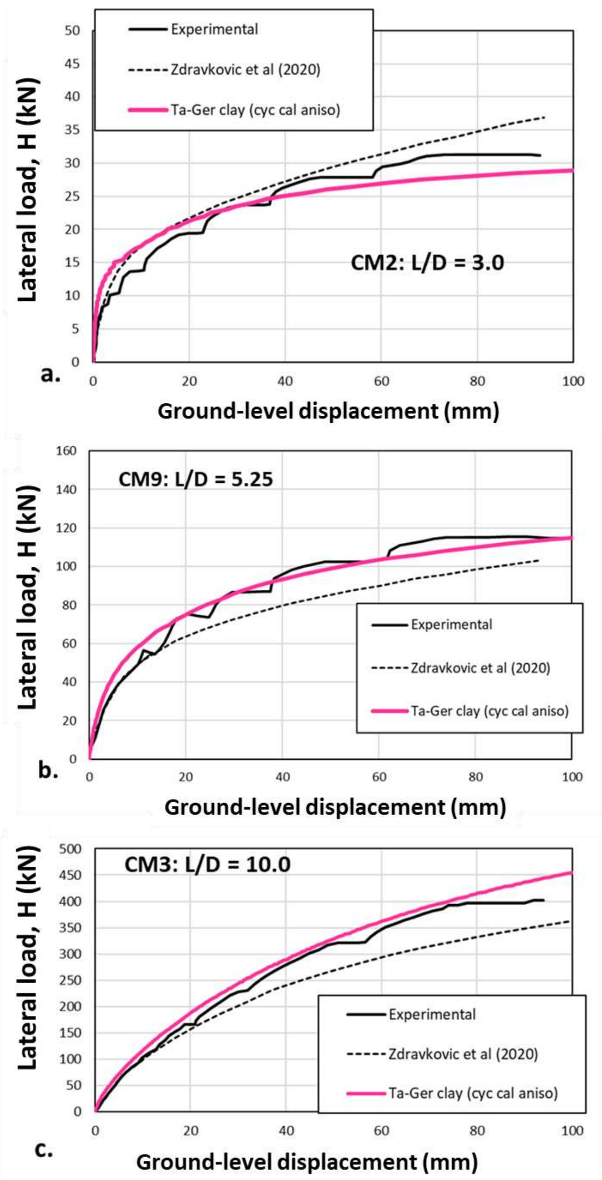

Figure 6. Numerical and experimental ground-level load-displacement curves for tests (a) CM2 (L/D=3.0), (b) CM9 (L/D=5.25) and (c) CM3 (L/D=10.0).

Figure 7 compares numerical and experimental data in terms of pile rotations and bending moments for monopile CM3 (L/D=10.0), respectively. Also plotted on the figure are the numerical predictions by Zdravkovic et al. (2020b) when available. Both comparisons (Figures 6 and 7) indicate that the numerical simulations conducted with a single set of calibration parameters reasonably reproduce the pile response measured in the field tests for a range of L/D ratios.

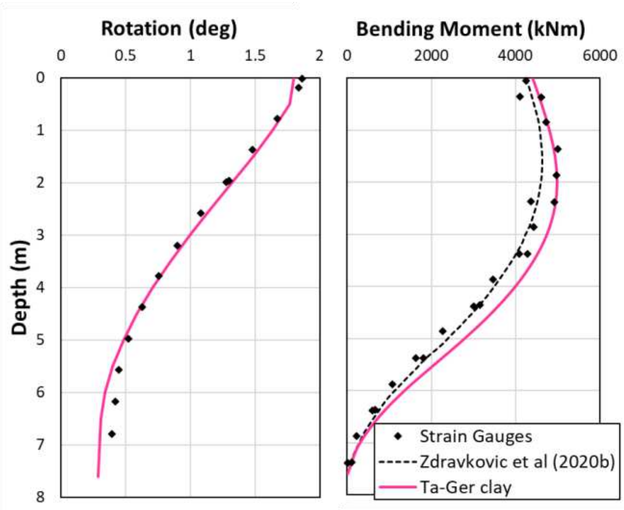

Figure 7. Experimental and numerical profiles of pile rotations and bending moments for test CM3 (L/D=10.0).

3.2 Cyclic Loading

Figure 8 compares numerical (red) predictions and experimental (black) data for the cyclic test CM6 in terms of moment-rotation loops. The comparison indicates that the numerical simulation captures very closely the accumulation of one-way rotation both in terms of amplitude and rate; or else ratceting effect due to asymmetric loading. Within a given cycle of loading/unloading, the numerical analysis indicates a stiffer response than observed in the field. Most likely this would be improved in further back analyses given the scatter in the G_{max} obtained from in situ and laboratory data in the upper 4m (L=4m) and the associated uncertainty in the selection of G_{max} used for the analyses (Figure 3). However, this stiffer response does not affect the overall predicted deformations or the rate of accumulation of deformations.

4 CONCLUSIONS

The Ta-Ger constitutive model for clay implemented in the finite difference code FLAC 3D was used to simulate selected field tests of monopiles conducted as part of the PISA program. The piles were subjected to monotonic and cyclic lateral and overturning loads. The numerical methodology, extensively validated for sandy soil conditions (Tasiopoulou et al., 2020, 2021; Chaloulos et al., 2020, 2024), was also validated against these selected PISA field tests performed on clayey soil. The favourable comparison with test measurements, both qualitatively in terms of deformation mechanism (ratcheting and gapping between pile and clay) and quantitatively (rate, magnitude of deformation accumulation) highlight the potential for using these types of time-domain analyses for cyclic load evaluations. Such a development could increase the reliability of ULS and SLS evaluations required to optimize designs. Since the constitutive models can be calibrated with a limited set of high quality laboratory test results, they could also help reduce the volume of expensive and time-consuming advanced lab testing currently required by simplified contour diagram based methods currently being used.

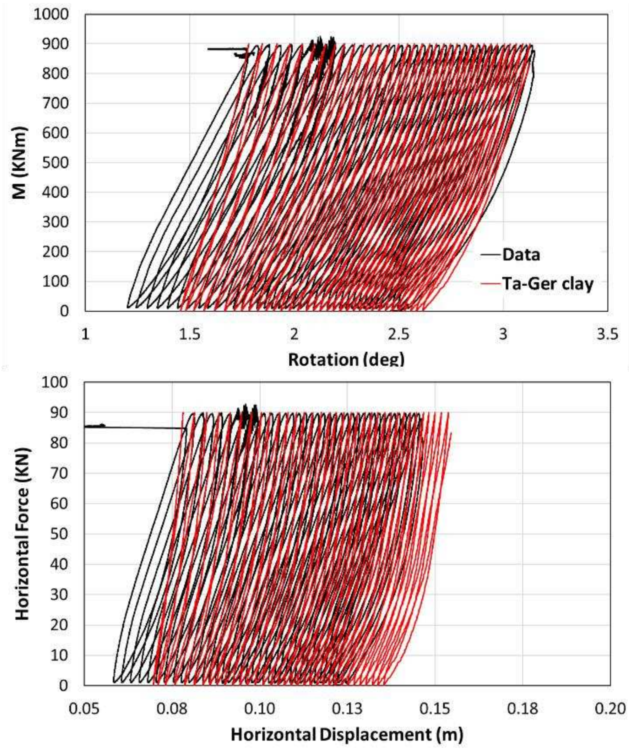

Figure 8. Experimental (black) versus numerical (red) data for cyclic test CM6 (L/D=5.25).

AUTHOR CONTRIBUTION STATEMENT

P. Tasiopoulou: Conceptualization, Methodology, Formal Analysis, Writing- Original draft. **T. Limnaiou**.: Software, Formal Analysis. **A. Giannakou**: Conceptualization, Reviewing and Editing. **J. Chacko**: Conceptualization, Reviewing and Editing.

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