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Numerical modelling by finite elements for a pile foundation under lateral cyclic action

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Abstract. The present paper is proposing to make a comparison between numerical results using Finite Element Method and experimental ones, for an isolated pile foundation in sandy soil, submitted to cyclic actions from wave or wind. 3D numerical modelling was performed in CESAR – LCPC software, using Drucker-Prager constitutive law with kinematic hardening for the soil. The small-scale centrifuge test results were obtained by IFFSTAR Nantes. The numerical and the experimental results, concerning the pile head displacements were in good agreement.

Keywords: Pile foundation; Lateral cyclic action; Numerical modelling; Small-scale centrifuge tests

1 INTRODUCTION

Off-shore structures, as for example oil platforms or off-shore wind mills, coastal structures or harbours, but also terrestrial structures are often submitted to cyclic lateral forces given by wind, waves, mooring forces or earthquakes. Such structures are usually built on pile foundations due to high forces to be transferred to the ground and also to the fact that usually are founded on grounds with soft, alluvial layers near surface.

The strong aleatory character of cyclic actions, which can also have an important dynamic component, is giving a high complexity to their approach. For this reason, the variable actions are often consider as equivalent to a static one (the pseudo-static method) and the cyclic parameters are ignored, which can lead sometimes to an unconservative design. Also, complex soil – structure interaction phenomena appearing are difficult to model.

For a better understanding of the behaviour of piles under lateral cyclic actions experimental models are needed. On international level the use of small-scale models tested in centrifuge is one of the best choices for analysing such foundations. Based on the experimental results, one can develop and calibrate numerical models to be used in design practice.

The objective of this paper is to develop a numerical model calibrated based on experimental centrifuge results. Those latest have been obtained from IFSTTAR Nantes (France), being carried out by Rosquoët between 2002-2004 (Rosquoët 2004).

The centrifuge tests were performed on a single pile in dry sand submitted to cyclic loading. Rosquoët (Rosquoët 2004) realized a couple of dozen tests, in which he varied four determinant parameters:

- Unit weight of the sandy soil (15.1; 16; 16.5 kN/m^3);
- Force applied on the pile's head (300; 450; 600 N);
- Amplitude of loading (150; 300; 450; 600 N);
- Number of cycles (from 12 to 44).

2 BRIEF PRESENTATION OF CENTRIFUGE TESTS USED FOR CALIBRATION

The scale used for the experimental program was 1:40, which implied a centrifugal acceleration of 40g. The main geometric and mechanical characteristics of the prototype and model pile are as follows (Rosquoët 2004):

Table 1. Characteristics of the prototype and small-scale pile

Prototype pile	Model pile
Tubular steel pile	Tubular aluminium pile
Pile length below soil surface D = 12 m	Pile length below soil surface D = 300 mm
Outer diameter B = 0.72 m	Outer diameter B = 18 mm
Inner diameter b = 0.685 m	Inner diameter b = 15 mm
Lateral force applied at 1.6 m above soil surface	Lateral force applied at 40 mm above soil surface
Young Modulus for steel $E_p = 2 \times 10^{11}$ Pa	Young Modulus for aluminium $E_m = 7.4 \times 10^{10}$ Pa
Inertial moment $I_p = 2.38 \times 10^{-3}$ m^4	Inertial moment $I_m = 2.67 \times 10^{-9}$ m^4
Bending stiffness E_pI_p = 476 MNm^2	Bending stiffness E_mI_m = 197.43 Nm^2

In order to pass from the prototype to the model the similitude conditions have to be kept, by working in multiple gravity and introducing a scale factor. The scale factors for the main physical parameters are the following:

Table 2. Main scale factors needed between the prototype and model pile (where N is the scale factor)

Physical dimension	Scale factor
Length: L	1/N
Displacement: ξ	1/N
Deformation: ε	1
Effort: σ	1
Force: F	1/N2
Bending moment: M	1/N3
Bending stiffness: EI	1/N4

The maximum force possible to be applied on the pile head, without having plastic deformations, was determined on aluminium samples and it resulted to be 600 N, which would correspond in prototype values to 960 kN.

The small-scale pile was instrumented using 20 levels of two gauges attached to the pile and mounted in half-bridge across the pile length. At the height of 25 mm above the soil and 20 mm below the soil surface, two displacements gauges were also attached.

Bending moment has been then computed and therefore the P-y curves (soil reaction – pile displacement at a certain depth) could be obtained, by double derivation and by double integration respectively.

The soil used for the experimental testing was the Fontainebleau sand with the main physical geotechnical parameters determined by Mécasol (Mécasol 1996).

3 DESCRIPTION OF THE NUMERICAL MODEL IN FINITE ELEMENTS

From the whole experimental program carried out by Rosquoët (Rosquoët, 2004), we have retained for the calibration of the numerical model, the experiment P355 with the following characteristics:

- Unit weight of the sand γ_d = 15.1 kN/m^3;
- Force applied on pile's head F = 600 N;
- Amplitude of loading DF = 300 N;
- Number of cycles n = 15.

The 3D numerical modelling was performed using the finite element software CESAR-LCPC (version 6.0, itech 2014) and it was carried out in small-scale values.

3.1 Geometry, mesh and boundary limits of the 3D model

The size of the model is 400 x 200 x 360 mm (chosen as such for reducing the calculation time), with a fixed mesh length density for outer boundaries of 60 mm. The pile had the same size as the experimental one, namely 340 mm of total length (300 mm below and 40 mm above the soil surface) and 18 mm outer diameter. The mesh density for the pile and pile-soil contact was 10 mm. The mesh creating function was a cubic with quadratic interpolation one. As for the mesh type we chose TETGEN mesh generator with Native surface mesh. Thus, we obtained a mesh with a total of 31171 nodes. Overall, the mesh was relatively large for the outer part of the sand mass, but very coarse for the contact pile-sand area (the most affected by the loading), as shown in the figure below.

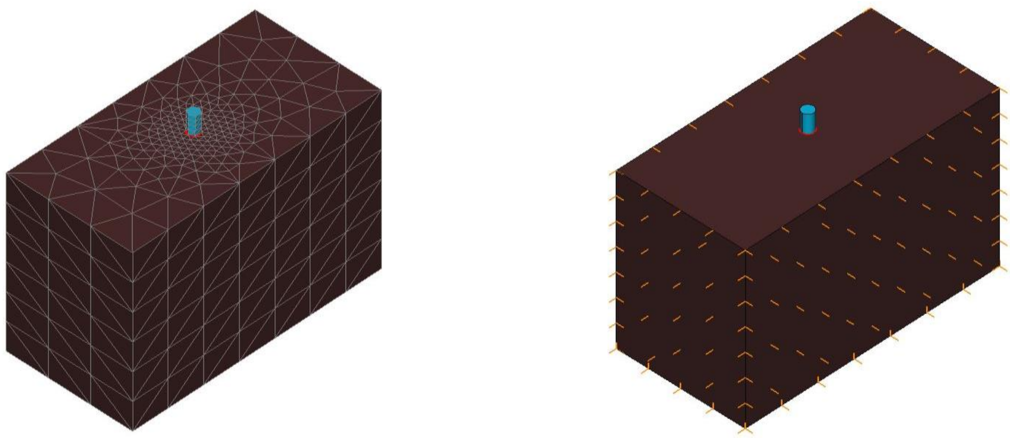

Figure 1. 3D view of the numerical model (left-mesh; right-boundary conditions) - (CESAR-LCPC**).**

3.2 Properties of the numerical model

The elasticity parameters considered for the pile were as follows:

Table 3. Pile properties used for the numerical model

Elasticity parameters	
Density:	ρ = 2700 kg/m^3
Modulus of deformation:	E = 3.83 x 10^{10} Pa
Poisson's ratio	υ = 0.3

The Young's modulus for the pile material is different than the one considered in the experiments, because in the numerical simulation we used a full circular section for the pile with a different moment of inertia ($\pi B^4/64$) in comparison with the moment of inertia for the tubular section ($\pi(B^4-b^4)/64$).

However, the bending stiffness EI = 197.43 Nm^2 should be the same in the numerical simulations as in the experiments. Therefore, keeping the same bending stiffness, but changing the moment of inertia, the Young's modulus of the material for the pile in the numerical simulations was 3.83×10^{10} Pa.

As for the sandy soil, we considered the following main characteristics for our model:

Table 4. Sandy soil properties used for the numerical model

Elasticity parameters	Plasticity parameters
Density: ρ = 1510 kg/m^3	Cohesion: c = 1 kPa
Deformation modulus: E = 30 MPa	Internal friction angle: $\Phi = 30°$
Poisson's ration: υ = 0.33	Dilation angle: $\psi = 30°$
	1st parameter of kinematic hardening law: C = 5 MPa
	2nd parameter of kinematic hardening law: D = 20 (dimensionless)

To simulate the plastic behaviour of the soil under lateral cyclic action we considered the Drucker-Prager with kinematic hardening constitutive law. The parameters C and D of the kinematic hardening law were chosen based on the results of some cyclic triaxial tests available in the literature (Rakotonindriana, 2009), tests over which it have been established that the ratio between these two parameters C/D has an important influence over the cycles and it should be comprised between 0.25 MPa and 0.30 MPa.

The soil-pile interface was modelled in two situations. In the first hypothesis we used a "Bond"-type contact element, for which we considered the lowest Young's modulus between the two materials, namely for the sandy soil E = 30 MPa. In the second one, we considered a "Perfect sliding" contact element, for which we considered the same lowest modulus of deformation between the two materials E = 30 MPa, with a simple traction strength R_t = 0 MPa.

3.3 Loading program and analysis type

In the first phase, we submitted the pile to a monotonic lateral loading in six increments (sub-steps) until reaching a value of F = 600 N. After that, we applied 30 cycles of unloading-loading (15 of unloading and 15 of loading) in three increments (sub-steps), with the amplitude DF = 300 N. The analysis was performed using the MCNL module of CESAR-LCPC (which solves a certain mechanical problem with non-linear behaviour) – particularly behaviour with components of MCNL (IMOD = 10000).

3.4 Numerical results in CESAR-LCPC

After the computation of the model, we obtained the following values (small-scale values) for the pile head displacements.

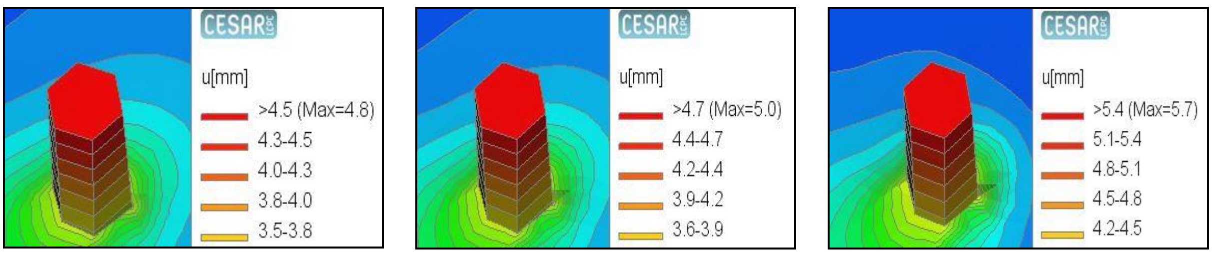

Figure 2. 3D results for pile's head displacements (left to right: end of monotonic loading, end of 1st cycle, end of 15th cycle – perfect sliding interface).

Figure 2 shows the maximum displacement obtained on the pile head using "perfect sliding" interface. On the left side is shown the maximum displacement at the end of the monotonic loading, which is 4.8 mm small-scale value (namely 192 mm prototype value) and on the right side the maximum displacement at the end of the 15th cycle with a small-scale value of 5.7 mm (or 229 mm prototype value). Thus, the maximum displacement at the end of the 15th cycle is 19% higher than the one obtained at the end of the monotonic loading.

Figure 3 presents the accumulation of displacements at pile head versus the applied force (prototype values – "perfect sliding" interface).

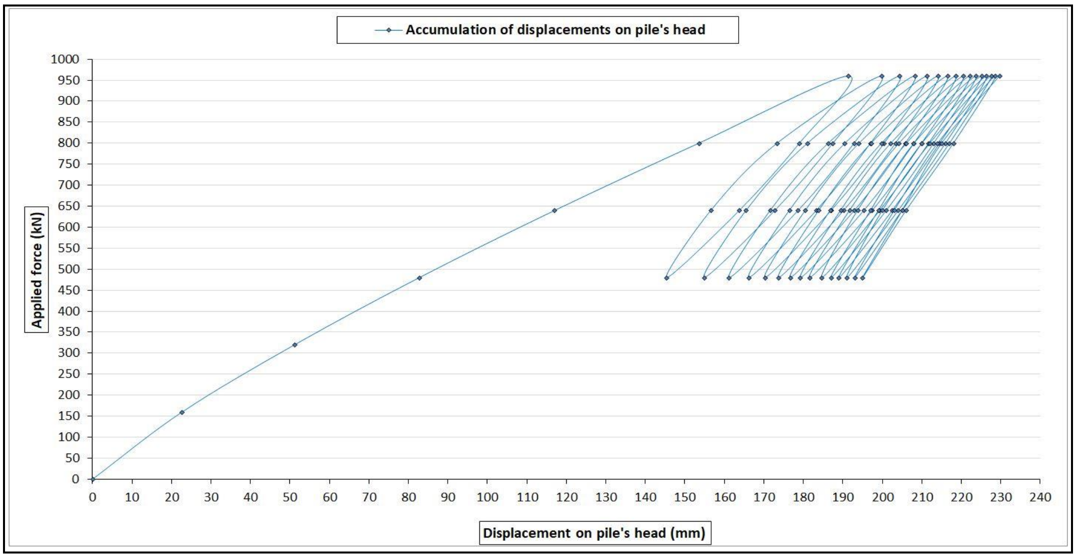

Figure 3. Accumulation of displacements on pile head (prototype values) – CESAR-LCPC.

Without the hardening law implemented into the classic constitutive law of Drucker-Prager, the numerical model couldn't simulate the accumulation of displacements shown above, obtaining only a simple line instead.

3.5 Comparison with centrifuge experimental test

The numerical values have been compared with the experimental ones.

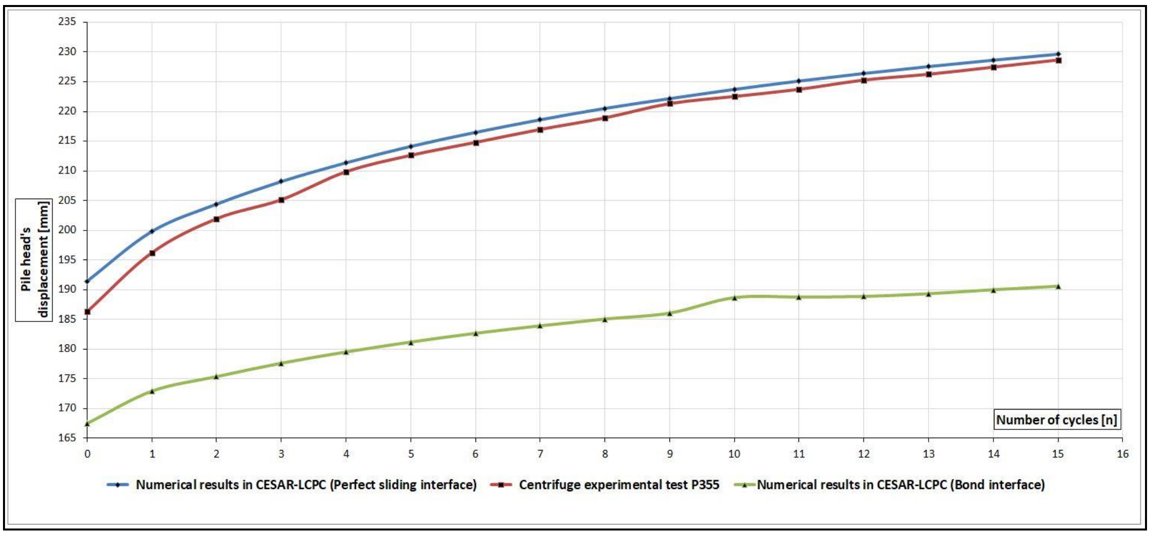

Figure 4. Accumulation of displacements on pile head with number of cycles (numerical vs. experimental).

Figure 4 shows the comparison in terms of pile head displacement versus number of cycles and it can be observed a very good agreement between the experimental and calculated values for the "perfect sliding" interface considered. On the other hand, for the "bond"-type interface considered the error between the numerical model and the experiment is relatively high, of 20%.

4 CONCLUSIONS

The design of structures submitted to cyclic lateral actions from wind or waves is a complex problem which requires consideration of a lot of factors. Such structures are often founded on piles. Under a certain series of loading-unloading cycles an accumulation of displacements is taking place on the pile head. Ignoring this accumulation could lead to unconservative design and, sometimes, to disastrous consequences for the future structures. The objective of the present paper is to develop a numerical model for simulating this cumulative behaviour, in order to be able later to model different types of situations. The numerical model was developed using the Finite Elements Method and has been calibrated based on small-scale centrifuge tests results.

The experimental test has been carried out at IFSTTAR Nantes, France by Rosquoët (2004) on a small-scale aluminium pile model installed in medium Fontainebleau sand and submitted to 15 loading – unloading cycles.

The numerical model was performed in the CESAR-LCPC finite elements software (version 6.0, ITECH 2014). The main challenge of the model consisted in implementing a hardening kinematic part to the classical Drucker-Prager constitutive law, in order to obtain the displacement accumulation during the cycles.

The obtained results showed a very good agreement between the experimental displacements at pile head and the numerical ones (229 mm numerical displacement at the end of the 15^{th} cycle and 228 mm experimental one – prototype values), for the "perfect sliding"-type interface. On the other hand, the numerical model perfectly simulates the decreasing of displacement accumulation with the cycles.

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