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# Numerical modelling by finite elements for a pile foundation under lateral cyclic action in sandy soil

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# Abstract

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 numerical modelling of the cyclic behaviour of soils and soil-pile interface under lateral cyclic actions is a very difficult task, in which, besides the fact that one must consider the irreversibility of soil deformations and the accumulations of displacements on pile head, the numerical model shall also consider the refined evolutions resulted from the succession of loading-unloading cycles with different amplitudes. An appropriate numerical modelling is greatly influenced by the choice of the constitutive model for the soil.

The purpose of the present paper is the study of the main parameters of influence which have an important role in the behaviour of pile foundations under lateral cyclic actions in sandy soils. Those parameters were grouped in 2 main categories: cyclic parameters (amplitude) and geotechnical parameters (volumetric weight, internal friction angle and modulus of deformation). This study has been performed by 3D numerical modelling using the finite elements software CESAR-LCPC (***itech, 2014***). The numerical model has been previously calibrated for a series of small-scale centrifuge tests obtained from IFSTTAR, Nantes, France, performed by Rosquoët (***Rosquoët, 2004***), for a maximum lateral force of 960 kN (prototype value) and 15 cycles.

***Key Words:***

Pile foundation; Cyclic action; Numerical modeling; Amplitude; Influence.

# 1 Centrifuge data used for calibration

The entire present 3D numerical modeling, regarding the behavior of a flexible pile submitted to lateral cyclic action in sandy soil, had as starting point the results of some small-scale centrifuge tests performed by ***Rosquoët*** at IFSTTAR, Nantes in 2004. The scale chosen for the tests was 1:40, implying a centrifugal acceleration of 40g.

The main geometrical and mechanical characteristics for the prototype and model piles are as follows:

**Tab. 1:** Main pile characteristics

| **Prototype pile** | **Model pile** |
|---|---|
| Tubular steel pile | Tubular aluminium pile |
| Pile length below soil surface D = 12 m | 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 |

In order to pass from prototype to model and vice versa, the similitude laws have to be kept, by working in multiple gravity and by introducing a scale factor N, which is 1/N for length and displacement, $1/N^2$ for the applied force, $1/N^3$ for the bending moment and $1/N^4$ for the bending stiffness.

The numerical analysis has been carried out in terms of small-scale model pile. However, in order to verify the scale factors mentioned above, another subsequent 3D model has been performed. The results between the prototype numerical model and the small-scale model (pile head displacement, pile deformed and bending moment in pile) showed an error inferior to 1%. Thus, performing the concerned 3D numerical analysis on the model pile was perfectly justified.

The maximum force that could be applied on pile head without having plastic strains has been determined on aluminum samples and was of 600 N (model value) or 960 kN (prototype value). The number of analyzed cycles was set to 15.

The soil used in the centrifuge experiments and also retained for the numerical model was the Fontainebleau sand with a unit weight varying from 14 to 17 kN/$m^3$, an internal friction angle comprised between 30 and 45° and a deformation modulus between 20 and 45 MPa.

# 2 Description of the numerical model

## 2.1 Choice of constitutive law for the soil

Cyclic lateral actions such as wind or waves represent, probably, the most complex way of action on a foundation, therefore an adequate constitutive law for the soil is required. Besides the fact that this model has to simulate the plastic behaviour of the soil, the most difficult aspect is certainly to simulate the accumulation of displacements on pile head.

Therefore, after a detailed study about this subject in the specialty literature, for the numerical modeling it has been chosen the Drücker-Prager law associated with a kinematic hardening law. The simple Drücker–Prager constitutive model, without associating a kinematic hardening law type couldn't simulate the displacement accumulation, the bending moment increasing or the degradation of soil strength with the cycles.

It is proposed to write the plasticity criterion as follows:

$f(\sigma) = F(\sigma - X)$, where: (1)

$F(\sigma)$ – initial plastic criterion of Drücker-Prager;

$X$ – variable tensor which evolves along the cyclic action and whose role is to take into account of the plastic displacement accumulation

$f(\sigma)$ – Drücker–Prager criterion associated with kinematic hardening.

The main challenge is to determine the tensor variable X. The simplest choice is the law proposed by ***Armstrong and Frederick, 1966***, implemented into CESAR software as:

$X = 0.67 \text{ x } C \text{ x } \varepsilon^p - D \text{ x } X \text{ x } \xi$, where: (2)

$\varepsilon^p$ – tensor of plastic strains;

$\xi$ – absolute value of the rate of plastic deformation accumulation, always positive, allowing the progressive accumulation of plastic deformations;

C (kPa) – first parameter of the kinematic hardening law;

D (-) – second parameter of the kinematic hardening law.

After solving a set of partial differential equations, one can state that the ratio C/D represents the difference between the deviatoric stress at soil's failure and its value at the end of the elastic zone. Based on the information of some triaxial tests available in the literature performed by ***Rakotonindriana, 2009*** (medium dense sand) or ***Gaudin, 2002*** (very dense sand), the ratio C/D resulted in both cases close to 0.25 MPa. Subsequent numerical analysis showed that the separate values of C and D do not have an important role, the ratio C/D being instead the one with most influence over the results.

## 2.2 Geometry and properties of the numerical model

The size of the model was 400x200x400 mm (xyz) with a 60 mm mesh density for the soil mass and 10 mm for the pile and pile-soil interface. It resulted thus a model with a 31171 nodes. Another numerical model with 85249 nodes has been created, but there was no significant difference between them two concerning the results. Obviously, in order to reduce the computation time, the model with 31171 nodes has been chosen (as show in the figure 1).

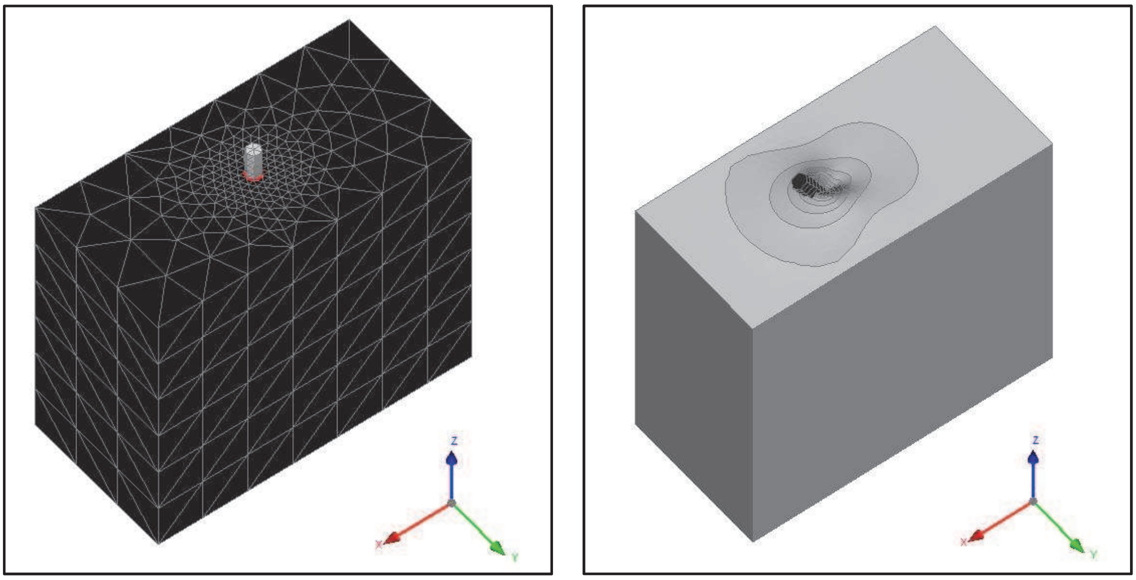

**Fig. 1:** Mesh mode (left) and deformed mode (right)

The pile has been considered free on the head, same as in the experiments. Soil-structure interaction in also very important when studying such a complex phenomenon. The chosen contact element between the pile and the soil was a perfect sliding type, with nil traction strength.

As for the analyze procedure, for the first stage the pile has been submitted to a lateral monotonic load in six increments, until reaching its maximum value of F = 600 N (model value). Afterwards, 30 loading-unloading cycles were applied (15 unloading and 15 loading), of various amplitudes.

# 3 Obtained results

## 3.1 Cyclic parameters influence

Besides the number of cycles, the amplitude (DF) is a cyclic parameter which plays a key role in the behavior of a pile submitted to lateral cyclic action from waves of wind. In order to analyze the influence of the amplitude on the displacements and bending moments for a single pile laterally loaded with 15 cycles, 4 numerical modeling were performed, each one corresponding to a amplitude of 150 N, 300 N, 450 N and 600 N. The geotechnical parameters of the sandy soil used for these numerical analysis were: an unit weight $\gamma = 15.1$ kN/m$^3$, a deformation modulus E = 30 MPa and an internal friction angle $\Phi = 30°$. The numerical results obtained using CESAR-LCPC software were:

### 3.1.1 Displacement accumulation on pile head

Analyzing the figure below one can immediately note that amplitude DF is playing an important role on the accumulation rate.

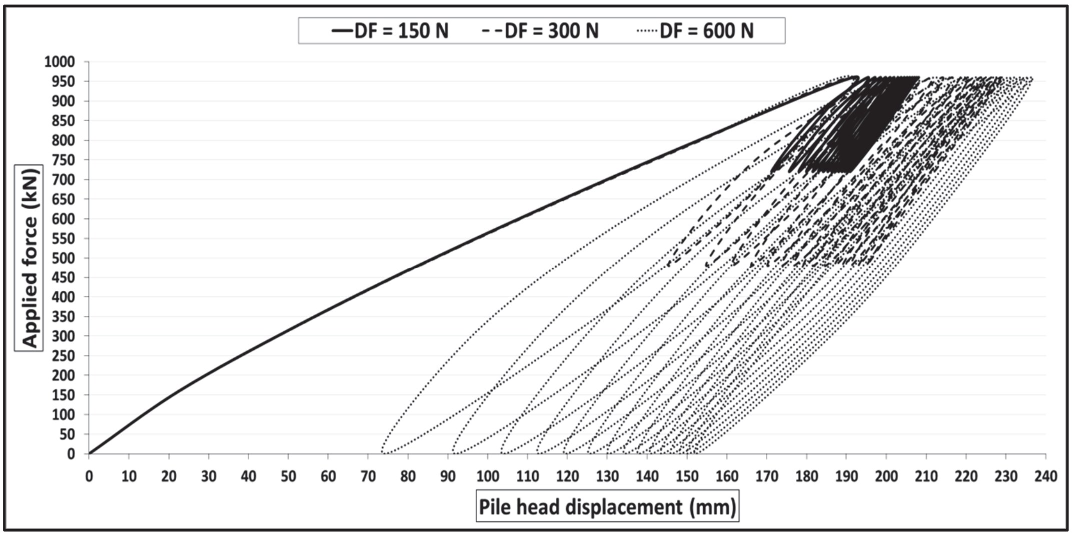

**Fig. 2:** Pile head displacement accumulation

Generally speaking, in all cases, whatever the considered amplitude, the displacement accumulation rate is maximum for the first 5 cycles, decreasing afterwards along the cycles. Higher the amplitude, larger the surface of hysteretic loops, therefore also higher the rate of displacement accumulation. As well, for low amplitudes, the hysteretic loops are smaller and the rate of displacement accumulation is much low. In the same time, for low amplitudes (DF = 150 N) it can be observed a relative stabilization of the displacements, while for higher amplitudes the displacement accumulation is still relatively pronounced even for cycle 15. Therefore, it can be affirmed that the most unfavourable situation regarding the displacement accumulation on pile head is the one for high amplitude (DF = 600 N) and a ratio DF/F = 1, respectively.

## 3.1.2 Displacement evolution on pile head

The graph below is in direct connection with the displacement accumulation on pile head, one being able to notice that the slope for 150 N amplitude is less steep than for higher amplitudes, indicating a faster stabilization of displacements.

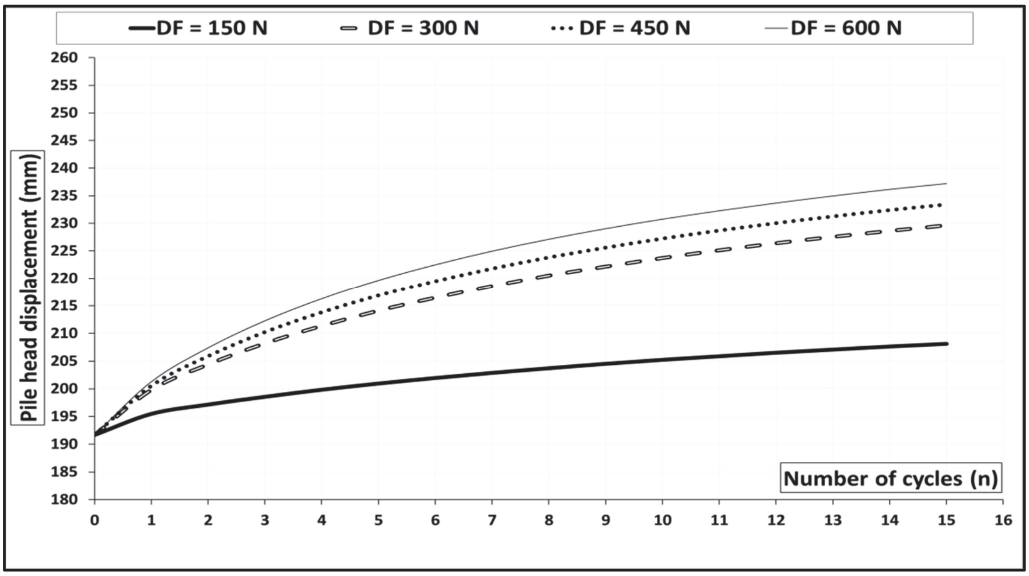

**Fig. 3:** Displacement evolution on pile head with cycles

Differences between maximum displacement on pile head at cycle 15 for amplitudes DF = 150 N and 600 N are quite large, of around 15%.

## 3.1.3 Bending moment diagram

Next figure presents the bending moment diagrams at the end of the 15 cycles. The portion 0 – (-2 m) represents the free length of the pile, while the portion (0-12 m) is the pile length below the ground level.

One can note that the difference between the 4 situations (amplitudes 150, 300, 450 and 600 N) is mainly in the maximum bending moment area, thus around 2.5 m depth.

The maximum bending moment developed in the pile is obtained this time for the lowest amplitude DF = 150 N, while the lowest bending moment is recorded for the highest amplitude DF = 600 N. The most logical explanation could be the densification of the sand for low amplitudes, resulting in a better soil and, therefore, a higher bending moment. For high amplitudes it is obvious that the sand cannot densify, resulting in a maximum bending moment at the end of the 15 cycles almost equal to the one at the end of monotonic stage.

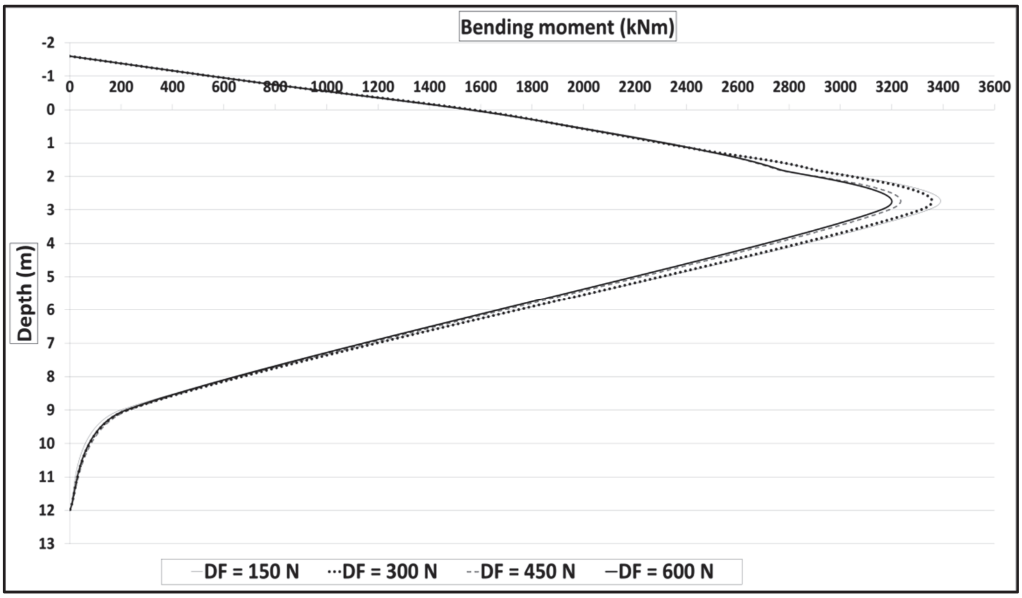

**Fig. 4:** Bending moment diagram for various amplitudes

However, between 150 N amplitude and 600 N one, the differences in maximum bending moment at cycle 15 are relatively small, of approximately 3-4 %.

## 3.1.4 Bending moment evolution along cycles

The next graph shows the evolution of the maximum bending moment along the cycles for the 4 considered amplitudes. It can be noted a higher increase of the maximum bending moment for the lowest amplitude, compared to the slower evolution of this one in case of maximum amplitude considered.

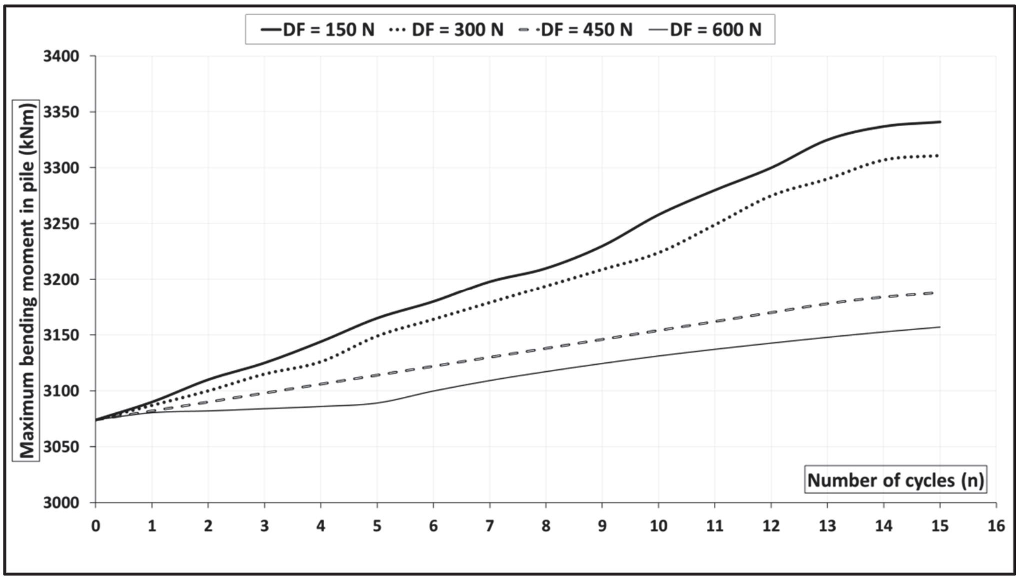

**Fig. 5:** Maximum bending moment evolution in pile along cycles

## 3.2 Geotechnical parameters influence

The soil mass plays a fundamental role in the analysis of a pile foundation submitted to lateral cyclic loads. Logically, better the soil, smaller the displacements. But this aspect should be analysed in detail, especially if considering the accumulation of displacement on pile head. The numerical analysis has been performed for a considered amplitude of 600 N, as being the most unfavorable from point of view displacement accumulation, as previously shown, for a number of 15 cycles. The analyzed soil has been considered in 3 situations, going from a less good soil to a very good one, as follows: loose sand ($\gamma$ = 15.1 kN/m$^3$; $\Phi$ = 30°; E = 30 MPa), medium sand ($\gamma$ = 16 kN/m$^3$; $\Phi$ = 35°; E = 35 MPa) and dense sand ($\gamma$ = 16.5 kN/m$^3$; $\Phi$ = 40°; E = 40 MPa). The exactly same model pile previously described has been used. The numerical results obtained using CESAR-LCPC software were:

### 3.2.1 Evolution of displacements on pile head

Analyzing the figure below one can note that the couples of values considered for the geotechnical parameters have a major role on the maximum displacements on pile head and also on their evolution along the cycles. It is interesting that the slope of the maximum displacement versus cycles graph is less steep for the good sand, which can be explained by a faster stabilization. It can therefore be affirmed that the better the soil, the faster the stabilisation of the displacements on pile head.

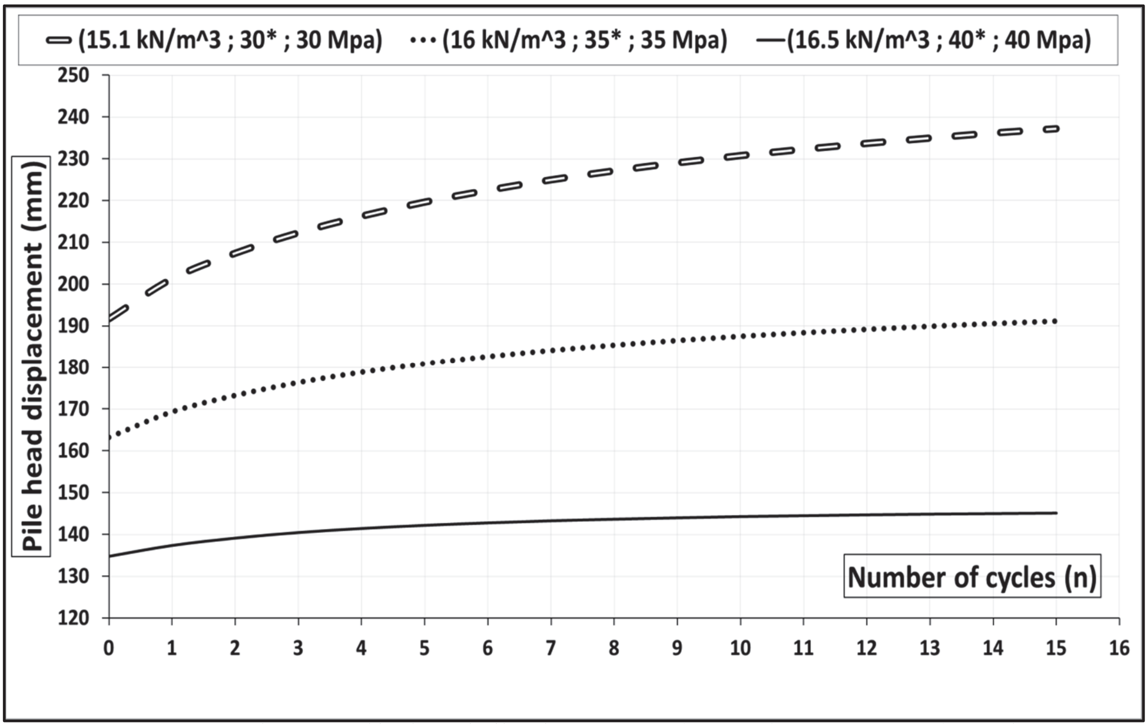

**Fig. 6:** Maximum pile head displacement for various types of sand

### 3.2.2 Evolution of maximum bending moment

The increase of the bending moment at the end of 15 cycles compared to the end of monotonic stage is, for all 3 cases, of 2.7% (for the considered amplitude of DF = 600 N). In the next graph is presented the evolution of maximum bending moment along the cycles for the 3 considered types of sand.

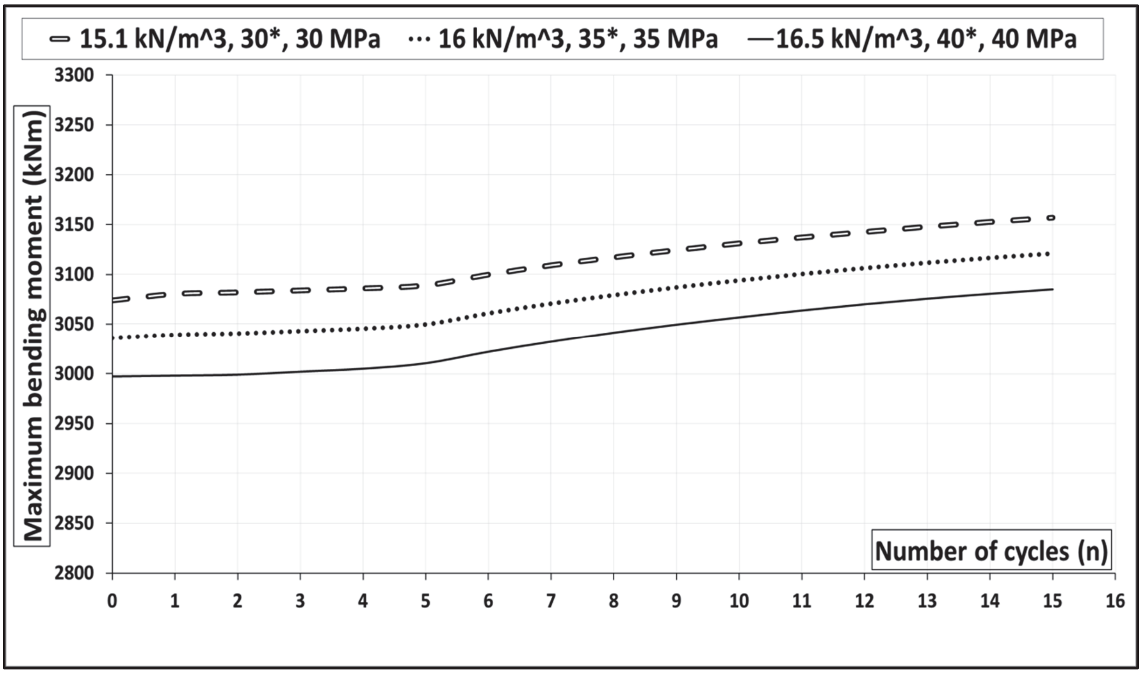

**Fig. 7:** Maximum bending moment evolution for various types of sand

It can be noted for all 3 cases that the evolution is practically the same.

## 3.3 Synoptic table - conclusion

Besides the results presented in the present paper, a series of another general parametric studies have also been performed in the CESAR-LCPC software, for all 4 amplitudes (150, 300, 450 and 600 N) and for all 3 types of sand (loose, medium and dense).

In the next table it is presented the general synthesis of the obtained results (increasing percentages from static to stabilisation cycle), regarding the maximum pile head displacement and maximum bending moment in the pile.

The stabilization cycles have been deducted using some extrapolation functions in CurveExpert software, starting from the initially considered 15 cycles.

The averages mentioned in the below table are justified in the context in which, in reality, along a very high number of cycles, it can't be exactly stated that the amplitude have been resting constant, but it can vary from a small value to its maximum value.

**Tab. 2:** General synthesis of the numerical modeling results

| Sand | DF (N) | Max. displ. on pile head (%) | Average (%) | Max. moment (%) | Average (%) |
|---|---|---|---|---|---|
| | | | | | |
| 1. Loose (stabilization at cycle 100000) | 150 | 35.3 | 37.7 | 10 | 7.6 |
| | 300 | 39 | | 9.4 | |
| | 450 | 39.4 | | 6.5 | |
| | 600 | 40 | | 5.2 | |
| | | | | | |
| 2. Medium (stabilization at cycle 10000) | 150 | 24.7 | 25.4 | 9.8 | 7.5 |
| | 300 | 25.1 | | 9.3 | |
| | 450 | 25.5 | | 6.6 | |
| | 600 | 26 | | 5.2 | |
| | | | | | |
| 3. Dense (stabilization at cycle 1000) | 150 | 8 | 8.5 | 9.6 | 7.4 |
| | 300 | 8.3 | | 9.1 | |
| | 450 | 8.6 | | 6.3 | |
| | 600 | 9 | | 5.2 | |

Neglecting these increasing percentages can lead to an inappropriate design of the pile foundation.

# 4 Literature

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