LARGE DIAMETER MONOPILE BUCKLING DUE TO LOCALIZED FORCE - A NUMERICAL STUDY

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ABSTRACT

In the last decade, the industry of fixed offshore wind farms has developed significantly, leading to important reductions of the global cost of the plants. Generally speaking, about 30% of the total cost of a wind offshore plant, including the installation activities, is related to foundations. In the view of optimising the management of the plant, strong efforts have been done to reduce the costs of the foundation, preserving the planned design while assuring a safe and reliable performance. From the practical point of view, the most diffused foundation, i.e., the monopile, is of special interest. Cost optimisation of the foundation suggests to increase the diameter and to reduce the wall thickness of the monopile, increasing the risk of pile tip damage, particularly frequent in soils where localized inclusions like flints or boulders are present. A higher potential tip damage is the undesired counterpart of the geometry optimisation and it may induce unacceptable economic consequences. This study, based on numerical analyses, is focalized on the buckling of the pile tip subjected to a variously inclined localized force, acting on the edge of the pile base. Results are collected in diagrams, which can be used in design procedures.

Keywords: offshore monopile foundation, pile driving, pile tip damage, buckling, shells, finite element modelling

INTRODUCTION

Nowadays, the offshore wind industry is considered a fully reliable and efficient production system and is aiming at further reducing the construction cost, in particular in Europe, where more than eighty percent of the total active offshore wind turbines are installed. The foundation represents a significant (about 30%) part of the total construction and installation investment, thus the reduction of the cost of wind turbine fields will involve certainly the optimisation of the installation of the foundation, today largely realized by means of driven monopiles with large diameters (Wang et al. 2018; Willis et al. 2018). The diameter is often larger than 6 m, with 12 m diameter not unusual. Pushed by the need of optimising the amount of steel and the cost, in a constant trend, the diameter to thickness ratio has increased considerably. This choice has increased the probability that impacts with boulders, eventually present in glacial tills, could damage the pile tip. Boulder impacts are undesired events that are becoming of strong relevance in the industrial environment, due to the severe consequences of pile tip damage on the monopile installation.

The increasing interest, in both scientific and industrial communities, for engineering problems related to offshore monopile foundations is testified by a few recent publications on the design issues of these systems: see, e.g., Li et al. (2011), Lombardi et al. (2013), Sheil and McCabe (2017), Zaaijer (2006). Similarly, regarding optimisation of costs and structural performances, recent studies and applications pay a growing attention to health monitoring, both in terms of structural assessment (Lozano-Minguez et al. 2011; Ziegler 2019) and of mechanical material characterization (Buljak et al. 2015).

As far as the structural buckling behaviours are concerned (Bažant and Cedolin 1991), however, the problem of tip damage in offshore pile foundations has not been sufficiently analysed in the current literature, revealing lack of knowledge and deficiency of methodologies able to address and mitigate the damage issues (Aldridge et al. 2005). A particularly important and underestimated aspect is the reliable estimation of the impact forces that develop during the pile driving in the presence of inclusions, e.g., flints and boulders. On this topic, recently Nicolini and Gargarella (2019) and Nicolini and Terribile (2020) have reported a few numerical studies.

In the present work, a Finite Element investigation is proposed to analyse the effect of localized forces applied at the pile tip with various inclinations. An assessment of consequent buckling phenomena is provided in order to provide possible safety thresholds with respect to pile tip damaging.

FINITE ELEMENT MODELLING

The numerical study presented herein has been developed with the commercial finite element code Abaqus (Abaqus Manuals 2017). The set of analyses is conducted in terms of a large parametric sensitivity analysis on eight diverse pile geometries, listed in Table 1. In order to minimize disturbance effects due to the boundary conditions, the length of the tube pile is set equal to five diameters.

Table 1. Geometrical and material properties of the analysed piles

Property	Value
Diameter D [m]	6.0, 8.0, 10.0, 12.0
Thickness ratio D/t [-]	80, 100
Imperfection [%]	± 2.0
Young modulus [10^9 Pa]	210.0
Poisson ration [-]	0.3
Yield limit σ_y [10^6 Pa]	420.0

The mesh discretization (see the Results section) has been chosen to obtain approximately squared elements, with a size corresponding to 6°-7° subtending arc. The finite elements used are four-node doubly curved shell element, with reduced integration and hourglass control, with finite kinematics (large strains and large displacements).

The material model to describe the steel is elastic-plastic isotropic, with linear behaviour up to yielding limit, and obeying the Huber-Hecky-von Mises yield criterion for perfect plasticity (see Table 1 for mechanical constitutive parameters).

In the numerical model the load is applied at a specific point located at bottom pile edge. Numerical analyses are conducted by imposing a prescribed displacement at the loading point and by acquiring the resulting reaction force. Numerical analyses are developed under displacement-controlled regime (maximum displacement equal to one quarter of the pile diameter), with five different force inclinations: horizontal, 1:2, 1:4, 1:6 and vertical. A more refined approach would consider specific contact conditions (boulder-pile) at loading points (Pandolfi et al. 2002); however, in the present study, the choice of an imposed force inclination appears to be the optimal one, since pile buckling represents the main concern to be tackled. Nonlinear analyses are carried out using the arc-length method (Riks algorithm) in order to properly control instability phenomena. Boundary conditions of the model are set in order to have the superior edge fully clamped, the nodes belonging to the half diameter of the inferior edge opposite to loading point simply supported in the longitudinal pile direction, with three additional nodes simply supported in the transversal direction along the edge opposite to the load, to control the rigid body motion (Fig. 1). The presence of soil surrounding the pile is not directly considered since the main focus of the study is centred on localized buckling phenomena at pile tip.

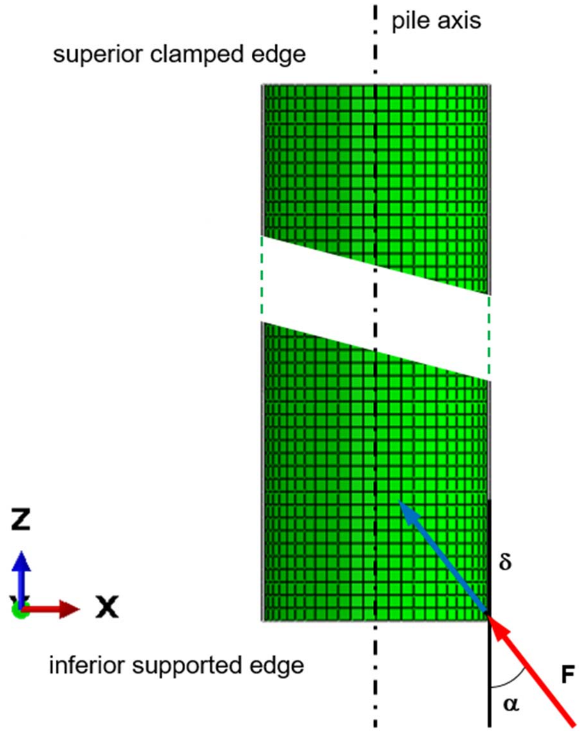

Fig. 1. Pile section geometry, boundary conditions and loading configuration system

As proposed in the COMBITUBE report (2014), in some analyses, the pile tube geometry is slightly modified, in order to describe potential imperfections, introducing a deviation of the vertical wall of the pile corresponding to 2% of outer diameter. Specifically, the straight geometry of the pile is consistently modified according to two cosine waves, the first along the circumferential direction (wave length equal to half circumference), the second along longitudinal direction (for the inferior half length; wave length equal to tube length). The sign of imperfection is set alternatively as "positive" and "negative", i.e., assuming that, at the loading point, the pile diameter may be increased or decreased. In a few additional analyses, another geometrical feature related to the definition of the mid surface of the shell is considered. Most of the analyses are developed assuming the actual mid-surface of the shell as reference for the meshing and loading. However, for the sake of comparison, some results are computed by assuming either the inner or the outer surface of the shell as reference for meshing and loading, therefore introducing additional loading eccentricity.

RESULTS

In the present section, in Figs. 2-6, a subset of the numerical results is reported in terms of plots of forces (F, normalised with respect to material yield limit and pile thickness) versus displacement (δ, normalised with respect to pile outer diameter).

Figs. 7-10 are extracted from normalised curves force versus displacement, choosing "peak" values as the initial peak point of each curve and "post-peak" values as the lowest point on the curve, after the respective peak. Fig. 11 represents, at varying force inclination angle (α), the evolution of loading reaction force and pile "damage" (quantified as diameter reduction Δ), at final stage of analysis, namely at imposed, consistently inclined, displacement equal to one quarter of pile diameter. An example of buckled pile with damaged tip is shown in Fig. 12, where the deformed shape is visualized and the colour map refers to the distribution of the von Mises stress.

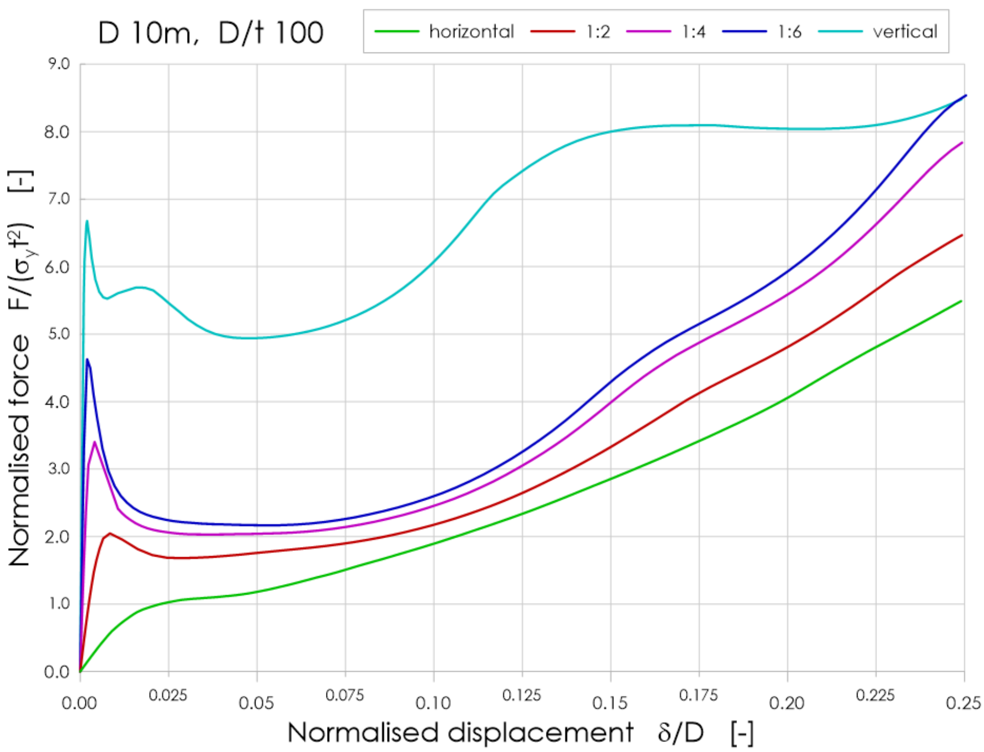

Fig. 2. Normalised force vs. normalised displacement curves for varying force inclination – pile outer diameter 10m, D/t ratio 100

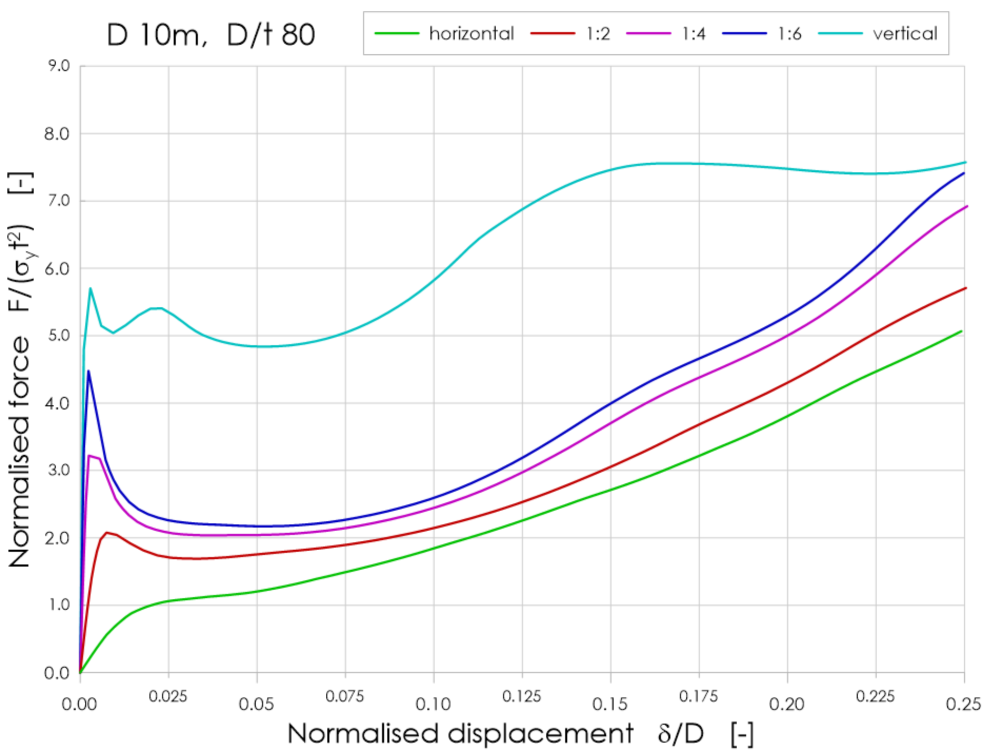

Fig. 3. Normalised force vs. normalised displacement curves for varying force inclination – pile outer diameter 10m, D/t ratio 80

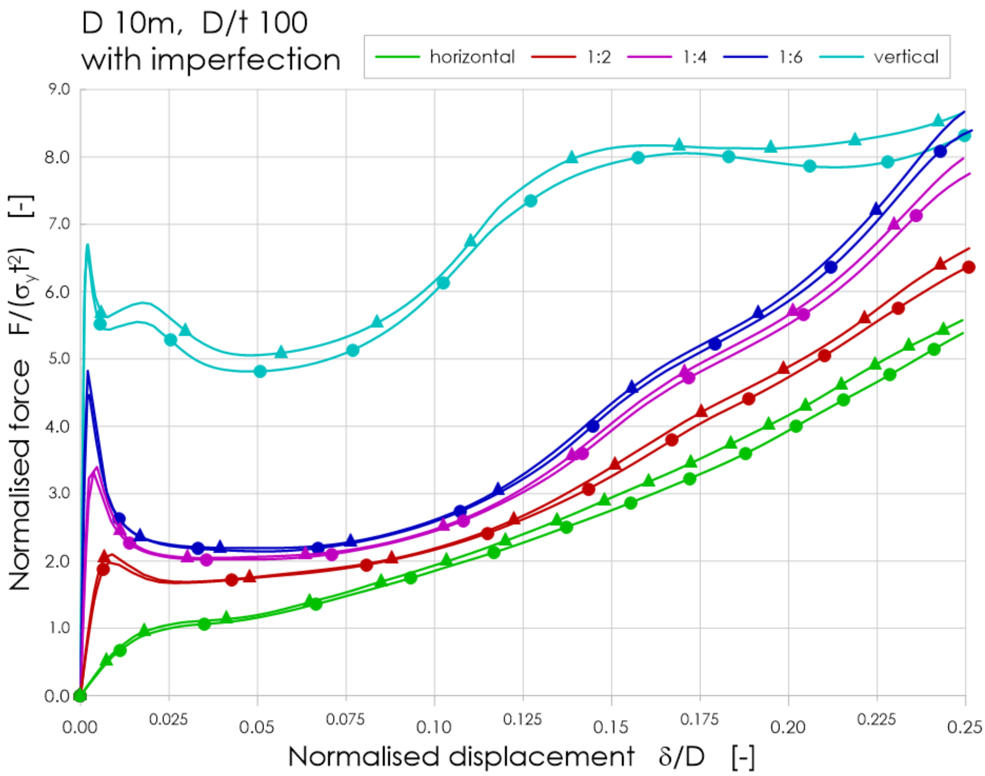

Fig. 4. Normalised force vs. normalised displacement curves for varying force inclination – pile outer diameter 10m, D/t ratio 100 – pile geometry with imperfection (positive with triangle symbol, negative with circle symbol)

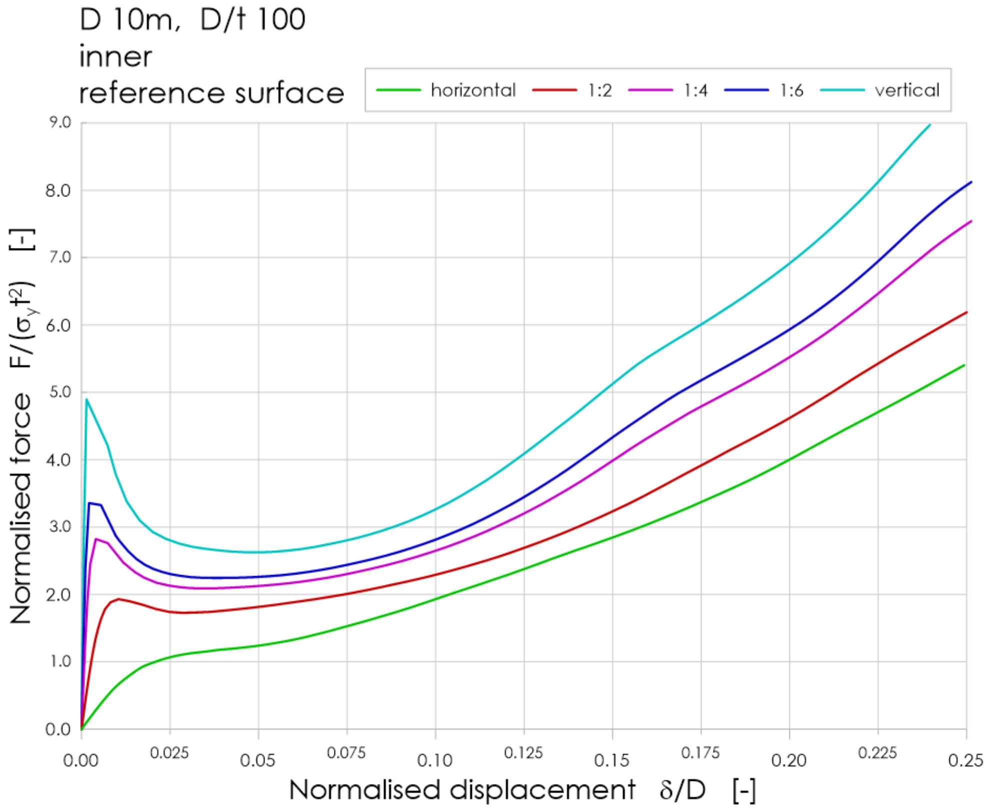

Fig. 5. Normalised force vs. normalised displacement curves for varying force inclination – pile outer diameter 10m, D/t ratio 100 – pile inner reference surface

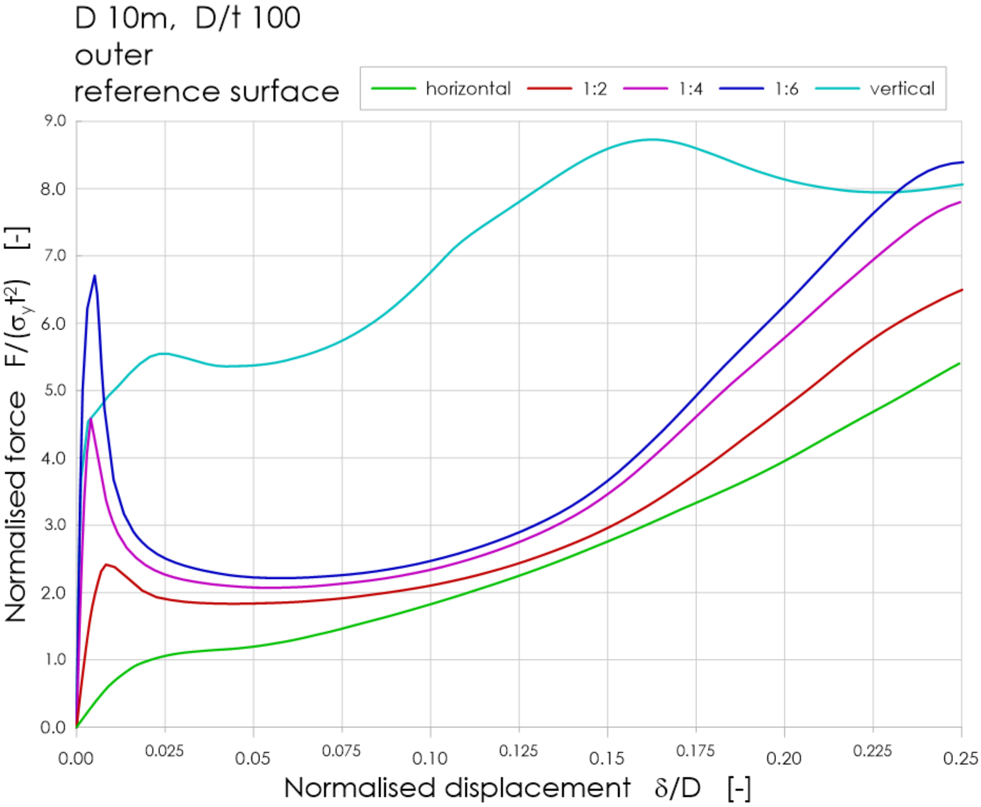

Fig. 6. Normalised force vs. normalised displacement curves for varying force inclination – pile outer diameter 10m, D/t ratio 100 – pile outer reference surface

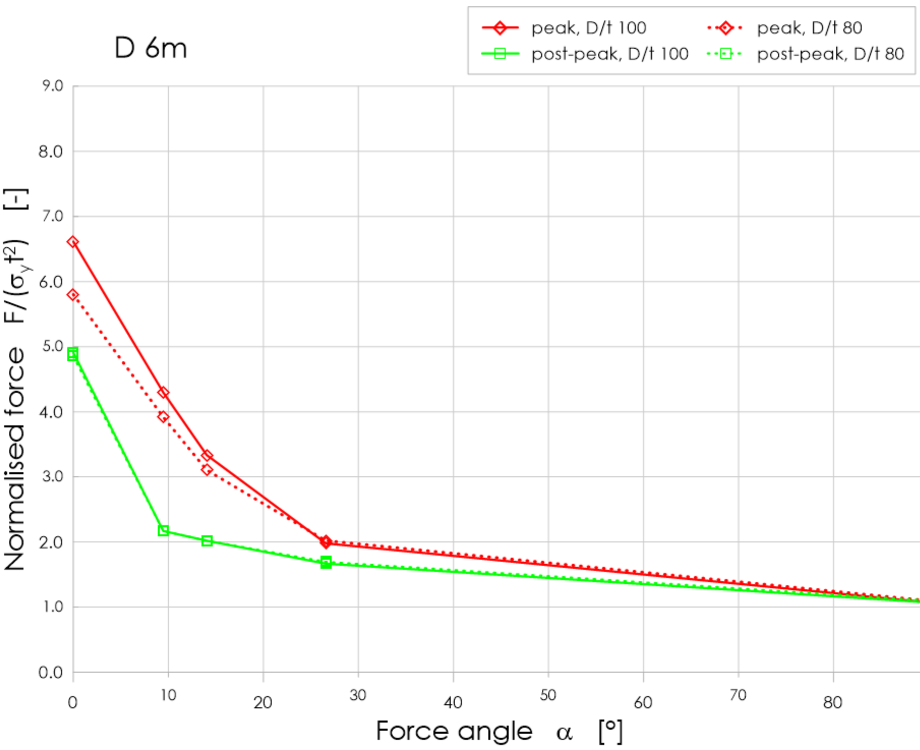

Fig. 7. Normalised force vs. force inclination; peak and post-peak values – pile outer diameter 6m

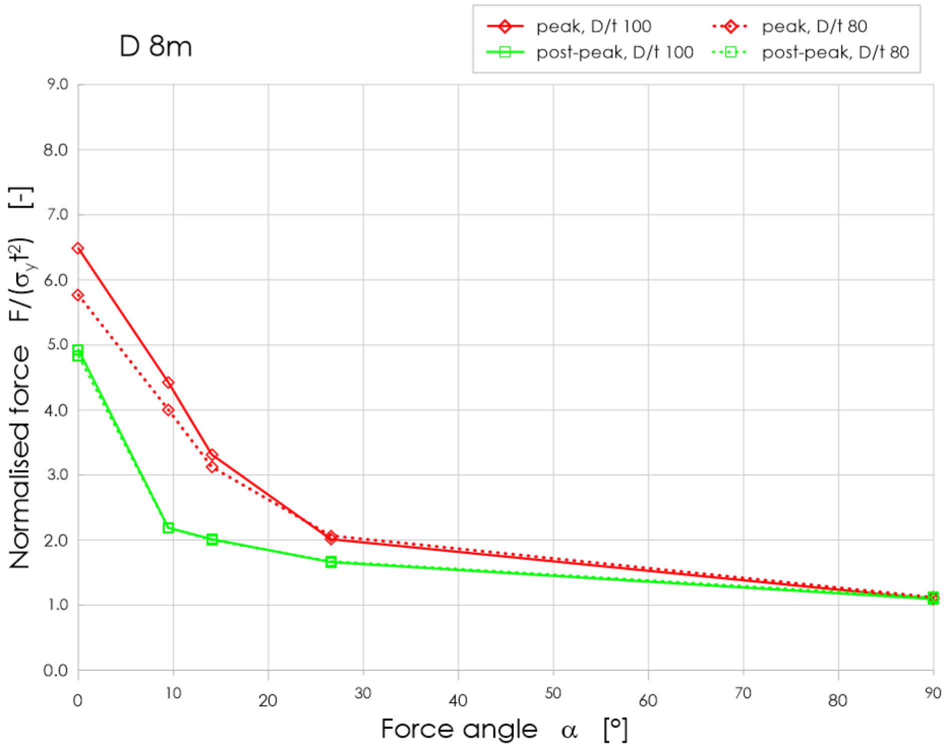

Fig. 8. Normalised force vs. force inclination; peak and post-peak values – pile outer diameter 8m

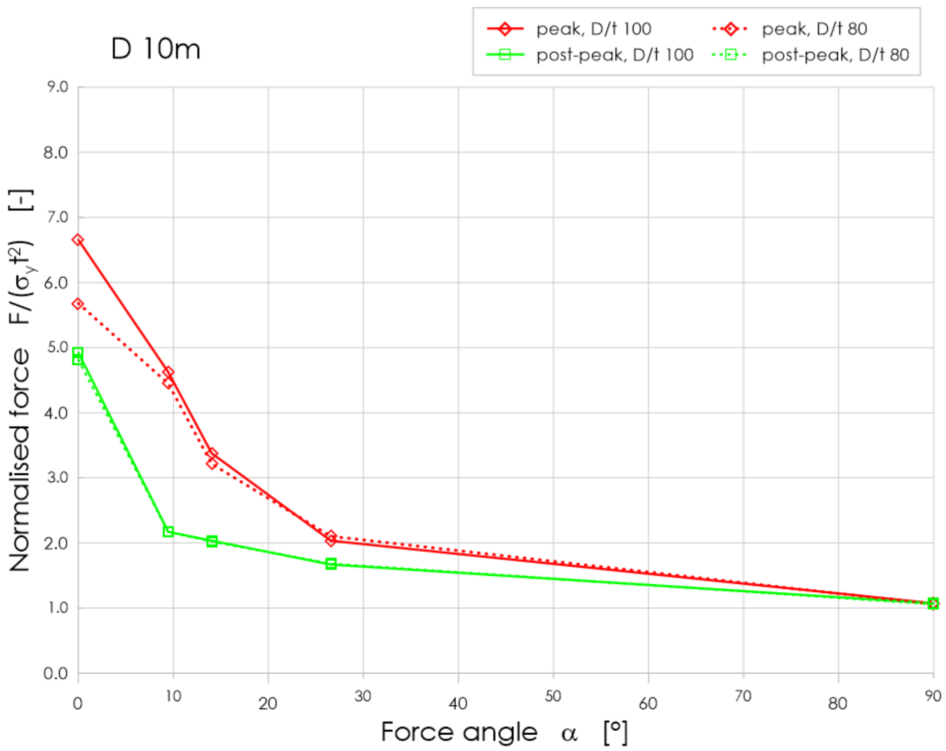

Fig. 9. Normalised force vs. force inclination; peak and post-peak values – pile outer diameter 10m

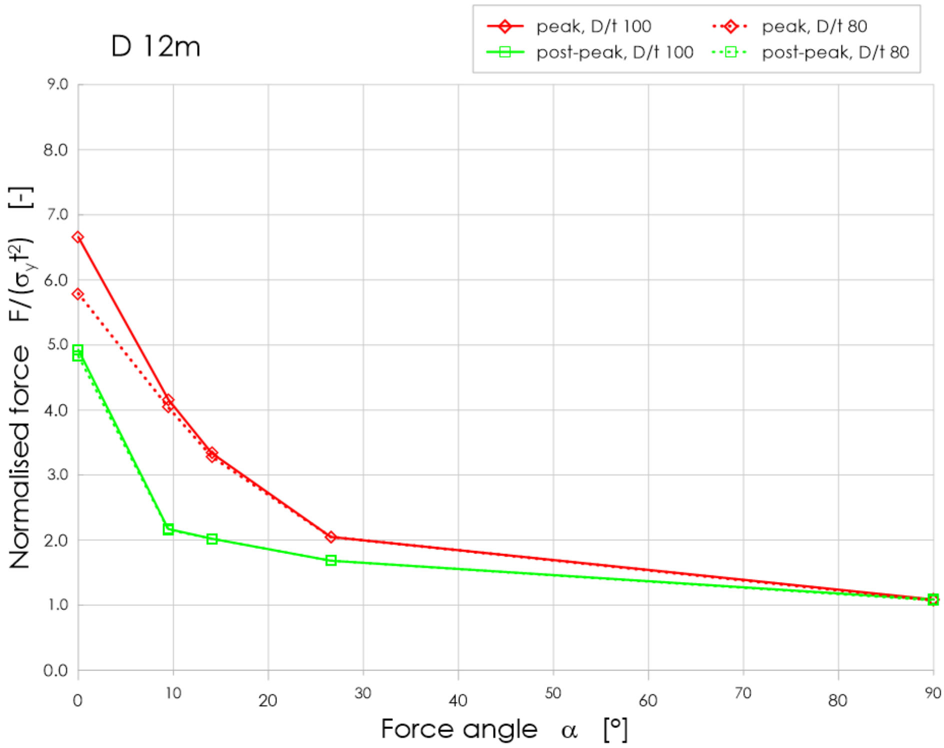

Fig. 10. Normalised force vs. force inclination; peak and post-peak values – pile outer diameter 12m

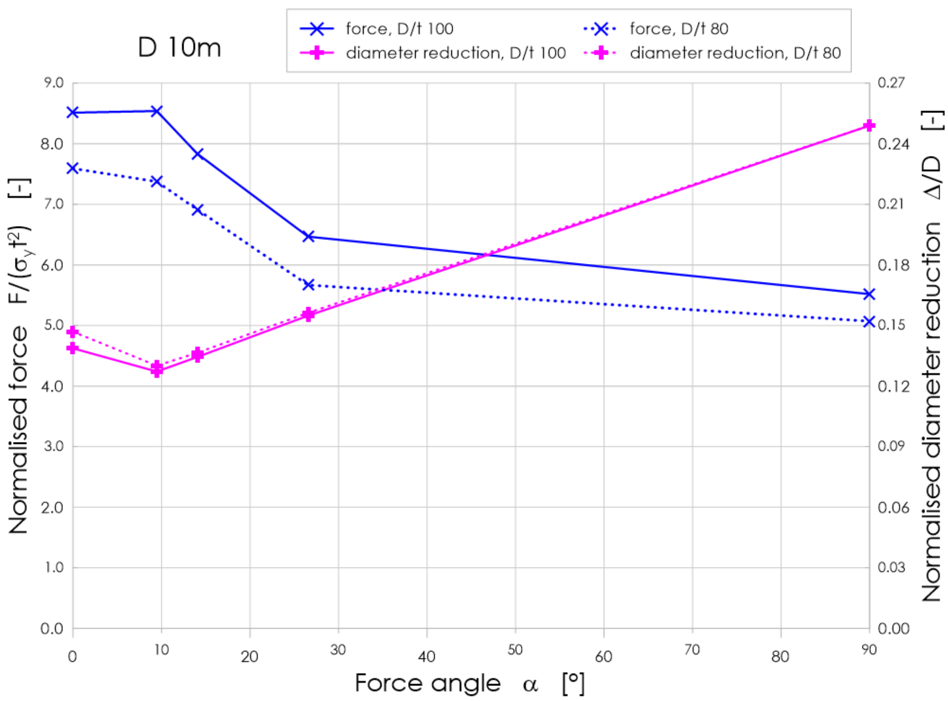

Fig. 11. Normalised force and normalised diameter reduction vs. force inclination (at analysis end) – pile outer diameter 10m

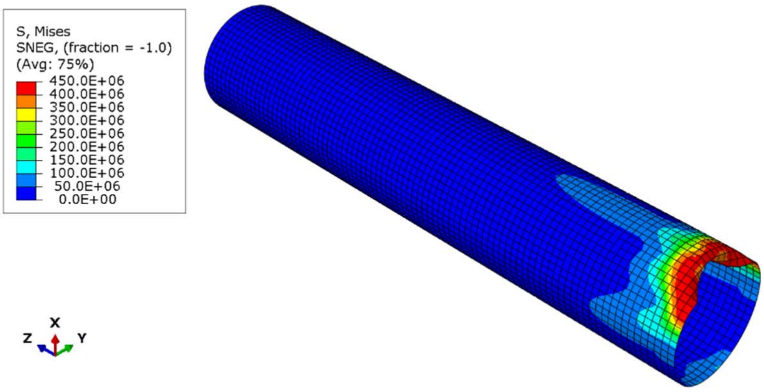

Fig. 12. Buckling failure behaviour – pile OD 10m, D/t = 100, 1:6 force; graphical representation of von Mises stress [Pa]

CONCLUSIONS

In the present study, several analyses have been conducted in order to understand the pile tip buckling phenomena at varying pile geometries and loading conditions. The comparison of numerical results, both from force versus displacement curves and from force versus angle charts, highlight common behaviours at varying outer diameter and diameter/thickness ratios. The most significant influence on load factor appears to be related to the inclination angle of the loading (impact) force. Interestingly, results address peak (usually attained for limited displacements, close to pile thickness) and post-peak values which may suggest that the practical pile residual strength is closer to the second values.

A remark concerns the case of imperfections, which only partially modify the results in terms of load factors. Therefore, values obtained on nominal geometries may be considered as reference ones, while cases related to imperfection may be interpreted as local disturbances leading to smoothing effects with respect to the peak load.

The force versus angle charts reveal that, for a given force inclination, the values of normalised load factors is almost not affected by the pile outer diameter and by the diameter to thickness ratio. Furthermore, the load factor is almost constant for horizontal force inclination, while some limited variation is exhibited at increasing force inclination up to the vertical one. Both horizontal and vertical conditions can be explained by focusing on the type of failure mechanisms induced by local instability of piles observed in the numerical analyses. In particular, for an assigned force inclination, similar failure mechanisms are observed in piles with different outer diameters and thickness ratios. Such similarities in failure mechanism produce, with proper normalisation by diameter and thickness, similar load factors. On the other side, the modification of the force inclination from horizontal to vertical induces different failure mechanisms: the horizontal force activates a simple bending behaviour, while the vertical force activates more complex behaviours characterized by local instabilities. The latter is clearly more sensitive to imperfection or variations of local disturbances, in particular for the peak load factor.

An additional positive conclusion can be derived by observation of post-buckling behaviours, which appear of hardening type, therefore on safe side for pile strength. It is worth to observe that such behaviour is shown for a buckling displacement up to one quarter of pile diameter, which already represents a significant level of damage at pile tip. Furthermore, the pile diameter reduction is related primarily to buckling bending and horizontal force components, and only secondarily is related to wrinkles in buckling behaviours.

As a practical outcome of the current research, the proposed charts appear to be useful in prediction, observation and mitigation of pile tip damage phenomena.

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