
Response of piles to inclined uplift loads

Influence of the soil-pile interface

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ABSTRACT. This paper presents a three-dimensional finite element analysis of the response of piles to inclined uplift loads. It deals with the influence of the soil-pile interface on this response. Calculations are carried out for several load's inclinations and different conditions at the soil-pile interface. The concept of the "critical depth" at the soil-pile interface is investigated. Analyses show that the lateral behaviour of the pile is independent from both the load's inclination and the interface condition, while both the load's inclination and the soil-pile interface largely affect the axial response of piles.

RÉSUMÉ. Cet article présente une analyse tridimensionnelle par éléments finis de la réponse d'un pieu soumis à une charge d'arrachement inclinée. Il comporte une étude de l'influence des conditions de contact à l'interface sol-pieu. Les calculs sont menés pour plusieurs inclinaisons de charge et diverses conditions d'interface sol-pieu. La notion de « profondeur critique » à l'interface sol-pieu est également étudiée. Les résultats des calculs montrent que le comportement latéral du pieu est indépendant de l'inclinaison du chargement et des conditions d'interface, tandis que la réponse axiale du pieu est fortement dépendante à la fois de l'inclinaison de la charge et des conditions d'interface.

KEYWORDS: bearing capacity, finite element, inclined load, interaction, non linear, pile, soil-pile interface, three dimensional, uplift load.

MOTS-CLÉS: capacité portante, charge chargement incliné, éléments finis, interaction, interface sol-pieu, non linéaire, pieu, tridimensionnel.

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1. Introduction

The response of piles to inclined uplift loads constitutes a major issue in the design of foundations of some structures offshore platforms, harbour structures, retaining walls, and transport structures. Centrifuge tests conducted on piles under inclined loads show that the lateral component of the load may significantly reduce the “axial” bearing capacity of piles (Meyerhof and Gosh, 1989, Sastry and Meyerhof, 1994, 1999, Meyerhof and Yalcin, 1994, Meyerhof, 1995). The experimental results also permitted the elaboration of semi-empirical methods for the calculations of piles under inclined loads. However, the generalisation of the obtained results raises some difficulties related to the scale effect due to the fact that the length of real piles are largely greater than the length of tested piles.

Shahrour and Meimon (1989) analysed the response of off-shore piles to inclined loads using a three-dimensional non linear finite element model. Perfect bonding conditions were assumed between the soil and the pile. Numerical results showed the load’s inclination does not affect the piles lateral response, but it affects the piles axial response. Consequently, the design of piles under inclined loads requires specific analyses for the axial component. The lateral component can be analysed using methods proposed for the design of piles under lateral loads (Broms, 1964, Reeze *et al.*, 1974, Poulos and Davis 1980, Fleming *et al.*, 1992).

Since the piles behaviour strongly depends on the condition at the soil-pile interface, this paper presents analysis of the influence of this condition on the response of piles to inclined loads.

2. Numerical modelling

2.1. Geometry description and materials behaviour

Three-dimensional nonlinear analysis were carried out using the finite-element package ABAQUS (2004), which offers interesting facilities in contact condition. Figure 1 shows the problem under consideration. It concerns analysis of the response of a vertical pile to inclined uplift loads. The pile is assumed to be linear-elastic with the following characteristics: length $L_p = 15\text{m}$, flexural stiffness $(EI)_p = 625\text{ MN.m}^2$, axial stiffness: $(ES)_p = 15,000\text{ MN}$ and it is assumed to be governed by a linear-elastic behaviour.

The soil behaviour is assumed to be governed by an elastic perfectly-plastic constitutive relation based on the Mohr-Coulomb criterion with a non-associative flow rule given by:

$$f = p \sin \varphi + \sqrt{J_2} \cos \theta - \sqrt{\frac{J_2}{3}} \sin \varphi \sin \theta - C \cos \varphi \quad [1]$$

$$g = p \sin \psi + \sqrt{J_2} \cos \theta - \sqrt{\frac{J_2}{3}} \sin \phi \sin \theta \quad [2]$$

C , ϕ and ψ designate the soil cohesion, the friction angle and the dilatancy angle, respectively; p , J_2 and θ stand for the mean stress, the second invariant of the deviatoric stress tensor and the Lode angle, respectively. Their expressions are given by:

$$p = \sigma_{ii} / 3$$

$$J_2 = \frac{1}{2} s_{ij} \cdot s_{ij} \text{ where } s_{ij} = \sigma_{ij} - p \delta_{ij}$$

$$\theta = \frac{1}{3} \sin^{-1} \left(-\frac{3\sqrt{3}}{2} \cdot \frac{J_3}{J_2^{3/2}} \right) \text{ where } J_3 = \frac{s_{ij} \cdot s_{jk} \cdot s_{ki}}{3}$$

The soil deposit is assumed to be a dry loose sandy soil with friction angle $\phi = 32^\circ$, dilatancy angle $\psi = 10^\circ$, Young's modulus $E = 10 \text{ MPa}$, and Poisson's ratio $\nu = 0.3$.

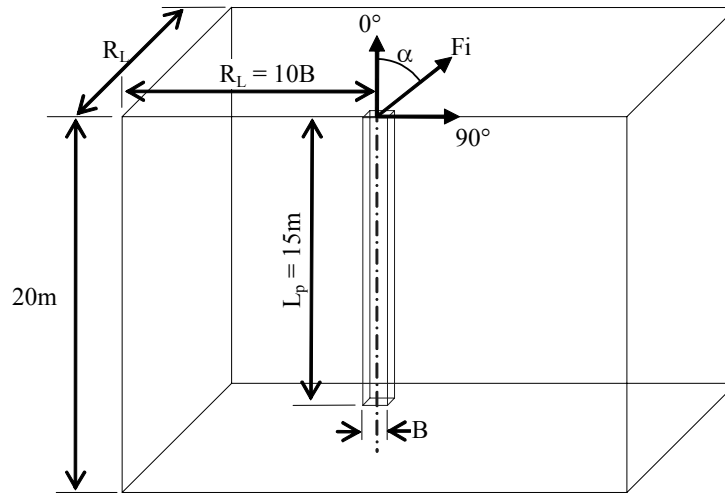


Figure 1. Pile under inclined load - geometry description

2.2. Finite element model

Figure 2 shows the mesh used in the finite element analysis. It includes 5 435 hexahedral elements and 6 989 nodes (20 508 dof). Preliminary analyses allowed for the determination of the lateral extension of the finite element model

(R_L). They showed that with a lateral extension $R_L = 10B$ (B denotes the pile width), the lateral boundaries do not affect the response of the pile to inclined loads.

Analysis is carried out for loads inclination with regard to the vertical axis (α) varying from 0° (axial load) to 90° (lateral load).

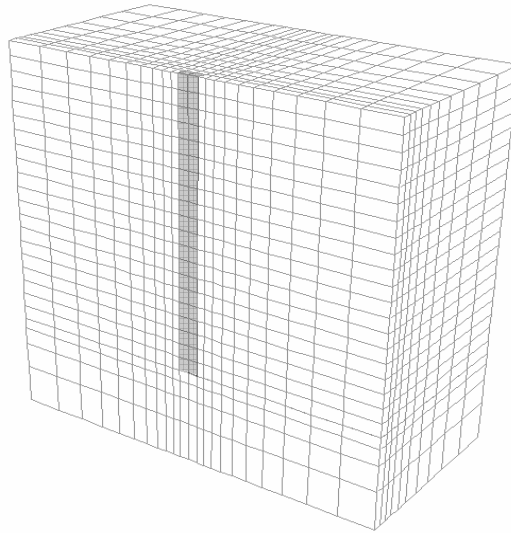


Figure 2. *Three-dimensional mesh using Abaqus (2004)*

3. Piles with perfect soil-pile bonding

This section presents an analysis of the influence of the loads inclination on the response of the pile with perfect bonding connection with the soil. Calculations were carried out for five inclinations $\alpha = 0^\circ$ (axial load), 30° , 45° , 60° and 90° (lateral load).

3.1. Pile displacements

Figure 3 shows the influence of the loads inclination on the displacement at the pile head. It can be observed that the displacement increases when the load approaches the horizontal direction. For a load magnitude $F = 1,500$ kN, the head displacement increases from $1.2\%B$ to $15\%B$ when the inclination α varies from 0° to 90° . This result indicates that the pile stiffness decreases significantly with the increase of the load inclination.

Figures 4a and 4b show the response of the pile in the vertical and lateral directions, respectively. It can be observed that the lateral response of the pile is

independent from the load's inclination, while the vertical response is affected strongly by the load's inclination. This finding agrees well with results obtained by Shahrour and Meimon (1989) on offshore piles. Figure 4c shows the influence of the loads inclination on the ratio between the lateral and vertical displacement. It can be observed that the lateral displacement is preponderant, in particular for high inclination, which means that the lateral flexibility of the pile is higher than the vertical flexibility. These results are confirmed by Figures 5a et 5b, which show the lateral δ_l (Equation [3]) and vertical δ_v (Equation [4]) flexibilities.

$$\delta_l = U_l / F_l \quad [3]$$

and

$$\delta_v = U_v / F_v \quad [4]$$

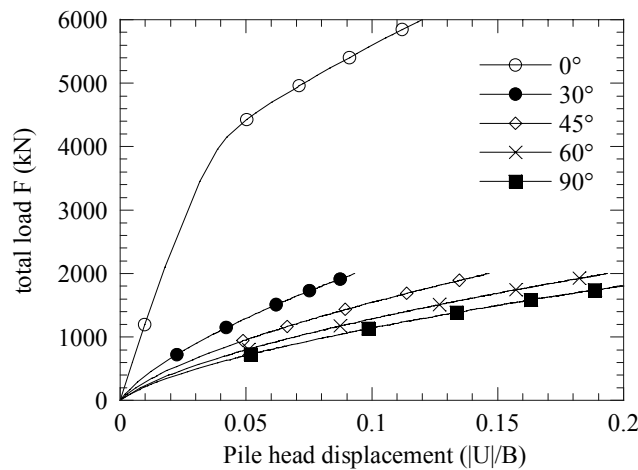
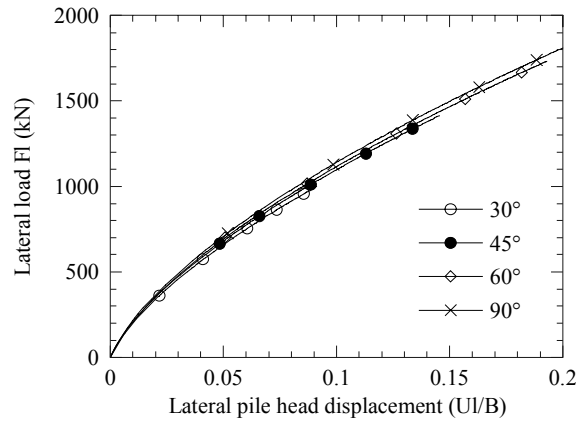


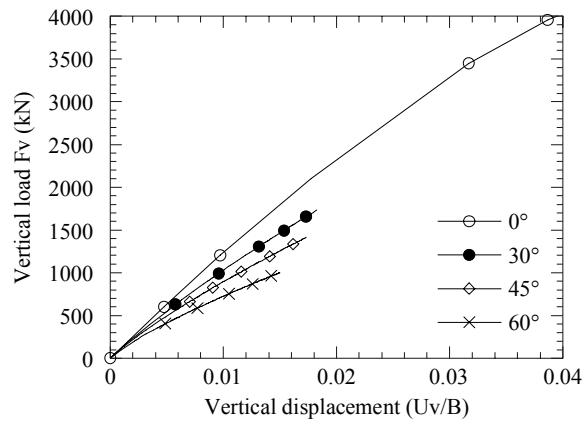
Figure 3. Displacement at the pile head

The lateral flexibility of the pile varies from 3.10^3 to 11.10^3 m/MN, while the vertical flexibility varies from $0.7.10^3$ to 2.10^3 m/MN. It can also be noted that the vertical flexibility is largely affected by the load's inclination, while the lateral flexibility is quasi independent to the load's inclination.

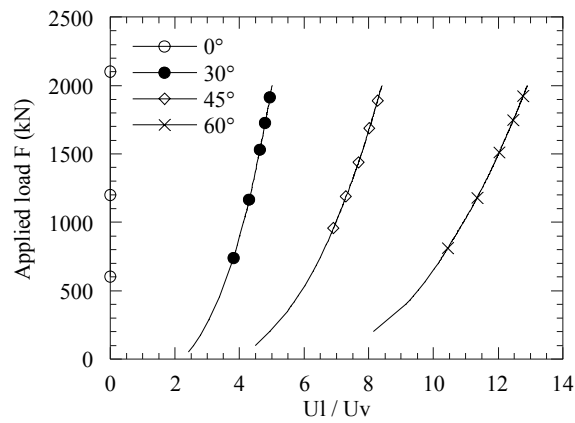
This result is due to the fact that the lateral load highly affects the stress distribution at the pile-soil interface which governs the vertical response of the pile; while the lateral response of the pile results from a mobilization of large zone around the pile, which is less affected by the vertical force.



(a) Lateral behaviour



(b) Vertical behaviour

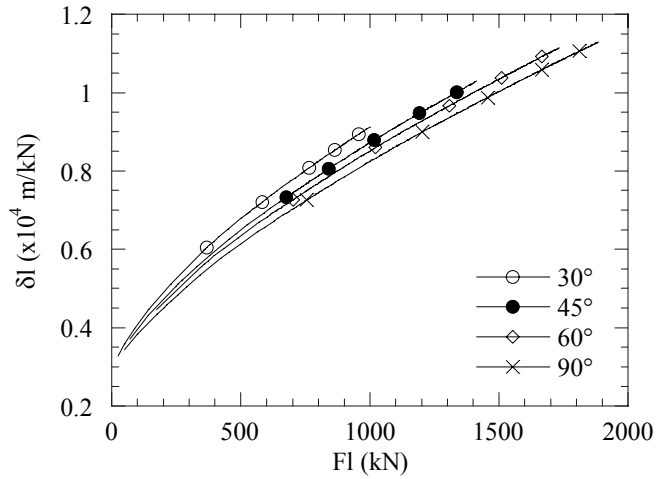


(c) Ratio lateral/vertical displacements

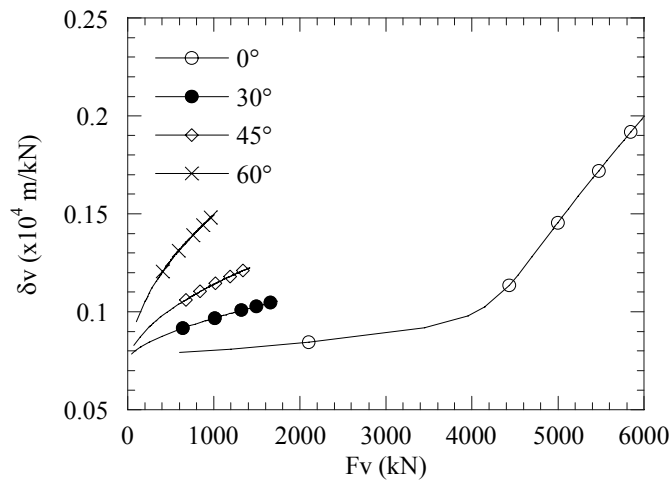
Figure 4. Variation of the displacement at the pile head

3.2. Spread of plastic zone

Figure 6 shows the extension of the plasticity in the soil mass for a same load magnitude $|F| = 2 \text{ MN}$ for all inclination loads. It can be observed that the inclined load induces plasticity almost around the pile head.



(a) Lateral flexibility



(b) Vertical flexibility

Figure 5. Evolution of the pile's flexibility

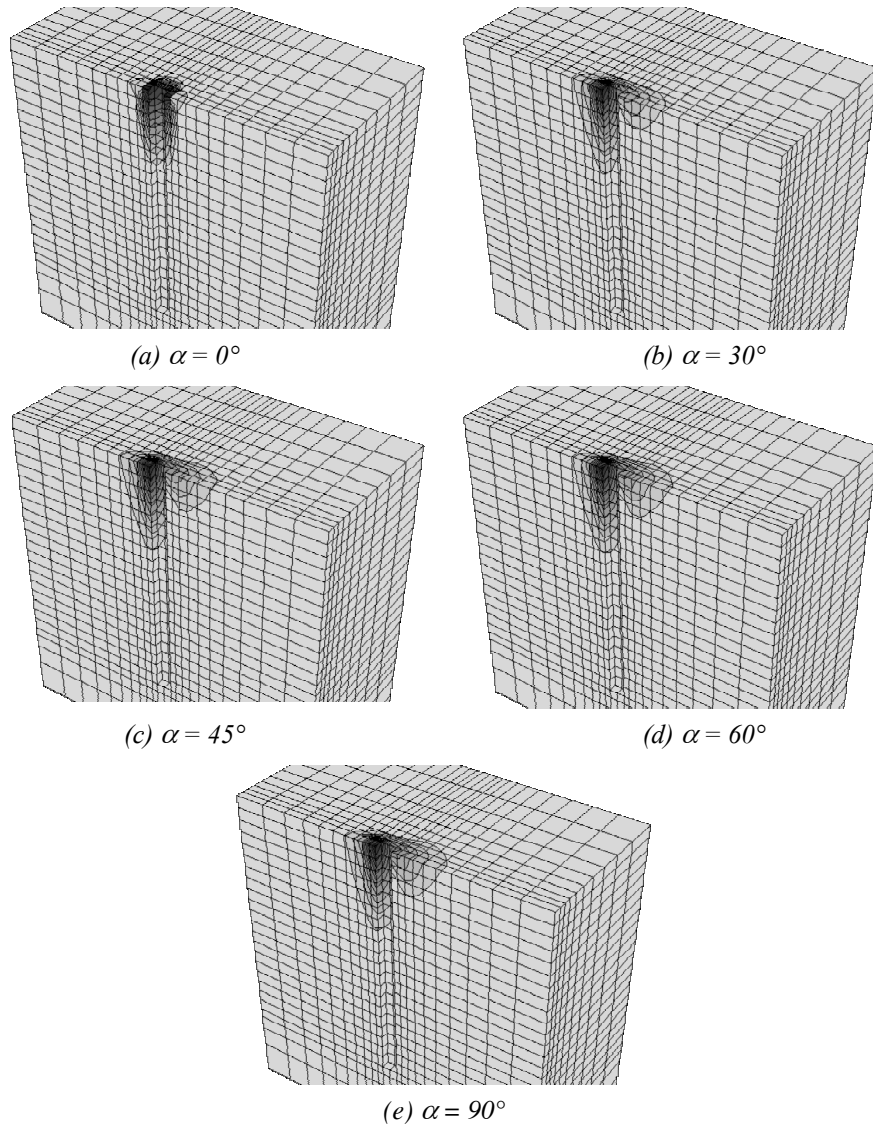


Figure 6. Development of plasticity for a magnitude of load $|F| = 2 \text{ MN}$

3.3. Internal forces

Figure 7a shows the influence of the loads inclination on the adimensional axial force N/F_v (F_v denotes the vertical component of the load). Two tendencies are observed:

- for the vertical load ($\alpha = 0^\circ$), the axial force decreases regularly with depth; this decrease is due to the friction at the pile's shaft;
- for inclined loads ($\alpha \neq 0^\circ$), the axial force increases with depth up to $Z = 6B$, then decreases. The axial force increase in the upper part of the pile indicates a negative friction which is due to the upward movement of the soil in front of the pile.

Figure 7b shows the distribution of the ratio between the bending moment (M) and the lateral component of load (F_l). It can be observed that the load's inclination does not affect the distribution of the bending moment.

3.4. Lateral soil pressure

Figure 8 presents the lateral soil pressure on the pile shaft, normalised by the lateral component of the applied load (F_l). It can be noted that the pressure is independent from the load's inclination. This result well agrees with the bending moment distribution. The pressure profile presents a maximum value at the depth $z = 2.5B$ and then decreases substantially and becomes negligible beyond the depth $z = 8B$.

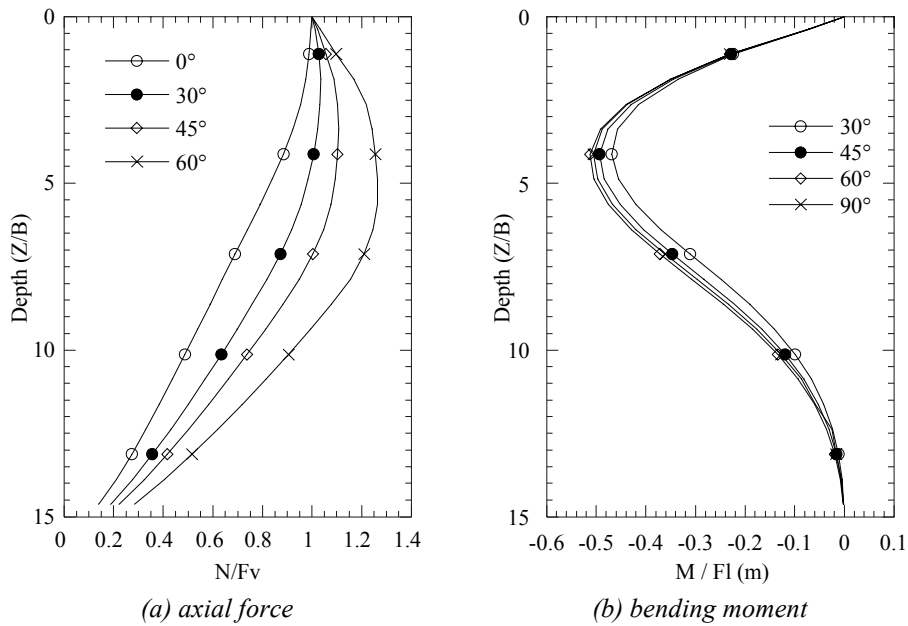


Figure 7. Internal forces acting on the pile

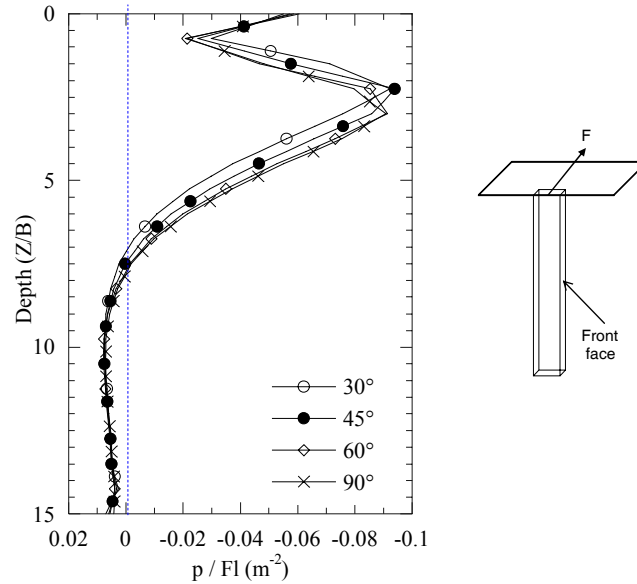


Figure 8. Lateral soil pressure acting along the front face of the pile

4. Piles with classical frictional interface

Since the response of piles to vertical loads strongly depends on the friction at the soil-pile interface, it is of major interest to take into consideration the interface condition in the analysis of the behaviour of piles under inclined loads.

Analysis was first carried out assuming a classical frictional model governed by the Mohr-Coulomb criteria:

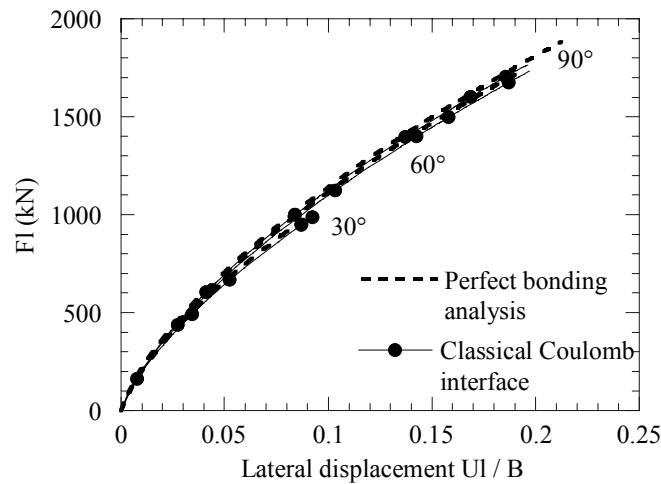
$$f = \tau + \sigma_n \operatorname{tg}(\varphi_i) = 0 \quad [5]$$

τ and σ_n denote the shear and normal stress at the interface, respectively; φ_i is the friction angle of the interface. Analyses are conducted with a frictional interface angle $\varphi_i = 32^\circ$, which is equal to the friction angle of the soil.

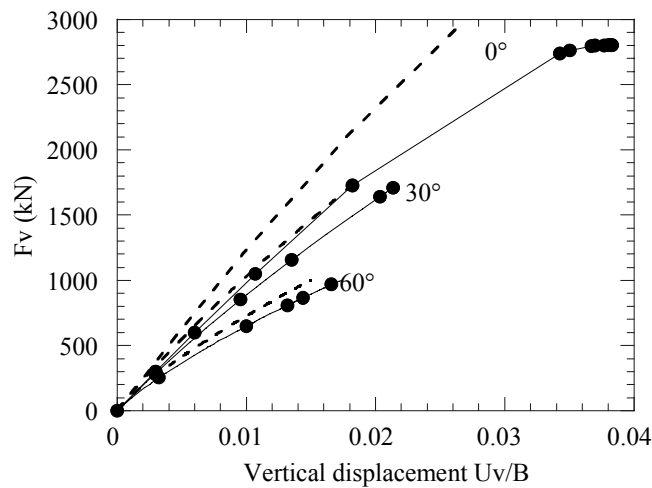
Figure 9 shows the influence of the load inclination on the relation between the load and the displacement at the piles head. It is can be observed that the load's inclination does not affect the response of the pile in the lateral direction, but it strongly affects the behaviour of the pile in the vertical direction. This result is similar to that obtained with perfect bonding at the soil-pile interface.

Figure 9 shows also a comparison between resultants obtained with frictional and perfect bonding at the soil-pile interface. It can be observed that the lateral response

of the pile is not affected by the interface modelling, while the vertical response of the pile is affected by the condition at the interface. The frictional interface induces a decrease in the stiffness of the pile. This result is confirmed by Figure 10, which shows that a frictional interface leads to an increase in the vertical flexibility of the pile.



(a) horizontal displacement at the pile head



(b) vertical displacement at the pile head

Figure 9. Influence of pile-soil contact condition using Classical Coulomb interface on the pile head displacement

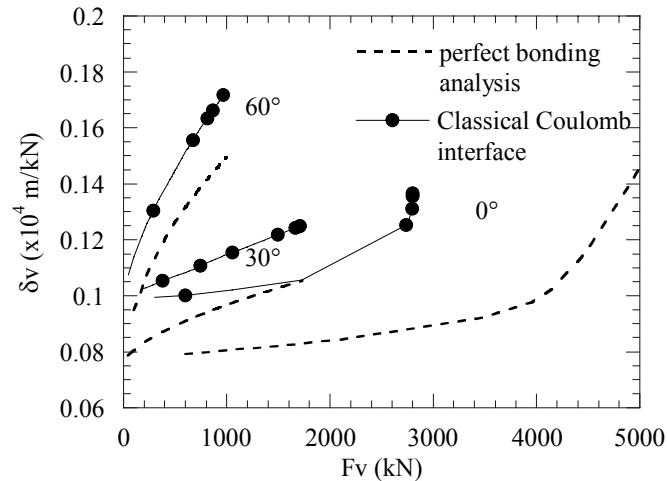


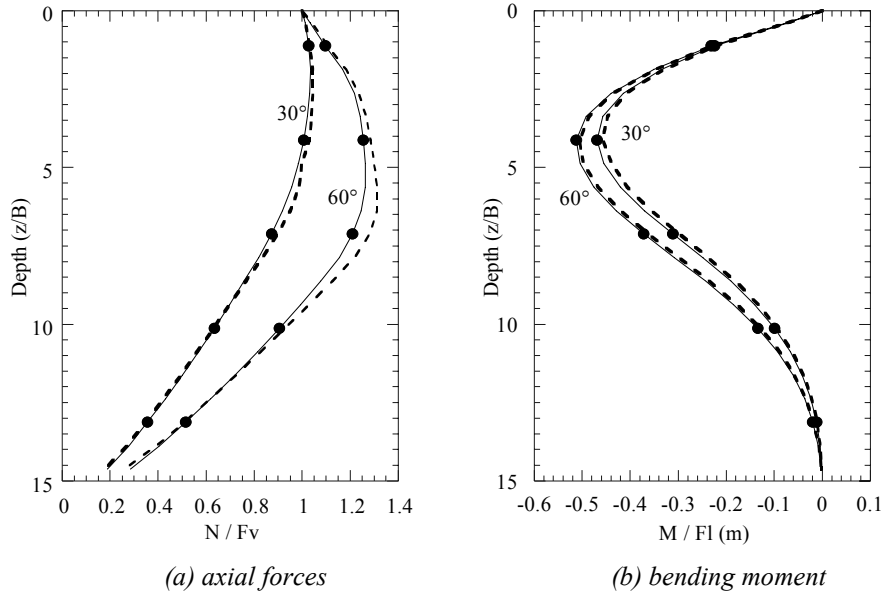
Figure 10. Influence of pile-soil contact condition using Classical Coulomb interface on vertical flexibility of the pile

Figure 11(a)-(c) show the influence of the interface condition on the internal forces and lateral soil pressure. It can be noted that interface condition does not affect the axial force, independently to the inclination. This result is also observed for the bending moment (Figure 11b) and lateral soil pressure (Figure 11c).

5. Interface with the “critical depth” concept

This section presents analysis of the response of the pile under inclined loads within the “Critical Depth” concept. This concept accounts for a realistic contact condition at the soil – pile interface. It is based on experimental results which showed the existence of a depth, called the “critical depth”, beyond which the shaft resistance remains roughly constant as shown in Figure 12 (Vesic, 1970, Hanna and Tan, 1973, Foray *et al.*, 1991, 1993, 1998, Lehane *et al.*, 1993, Randolph *et al.*, 1994, Hanna and Nguyen, 2003, API, 1984). It corresponds to the transition from a dilating behaviour of the sand at low pressure (depth) to a contracting behaviour at high pressure. According to Foray *et al.*, (1991, 1993), this two-level interaction behaviour may be physically explained by the transition from a highly dilating behaviour of dense sands at low pressure (depth) to a contracting one at high pressures. The critical depth depends on the pile installation, diameter, and the soil compaction (Coyle and Castello, 1981).

Calculations were carried with a critical depth $z_{crit} = 6B$, where B denotes the pile width.



----- Perfect bonding analysis
 —●— Classical Coulomb interface

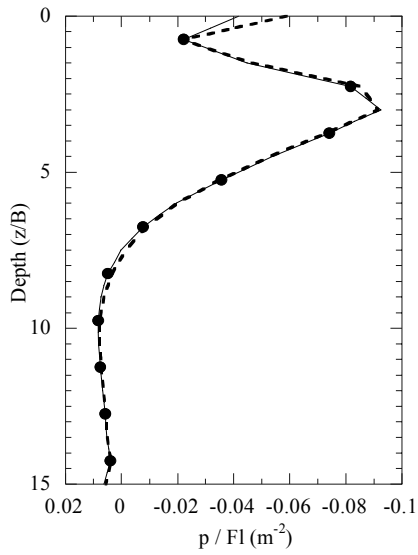


Figure 11. Influence of pile-soil contact condition using Classical Coulomb interface on internal forces and soil pressure

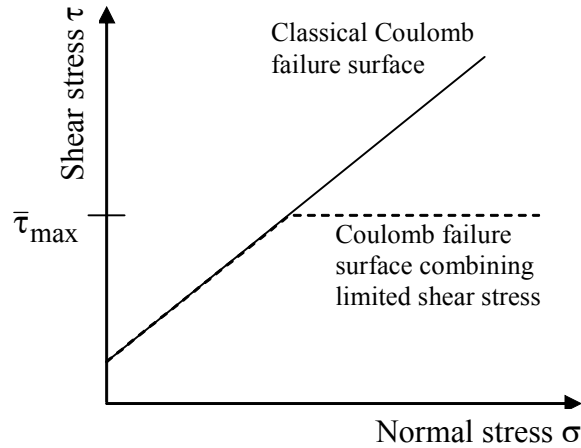


Figure 12. The “Critical Depth” concept at the interface

Since the load inclination affects only the vertical response of the pile, this section focuses on the vertical response of the pile. Figure 13 shows the influence of the load’s inclination on the response of the pile with the critical depth concept. It can be observed both the vertical displacement and flexibility are affected by the loads inclination. Comparison with results obtained with the classical interface, shows that the critical depth concept leads to an increase in the piles flexibility and to a decrease in the vertical bearing capacity. For the vertical load, the bearing capacity of the pile with the critical depth concept is equal to 1850 kN, which is equal to about 66% of the bearing capacity of the pile with the classical interface.

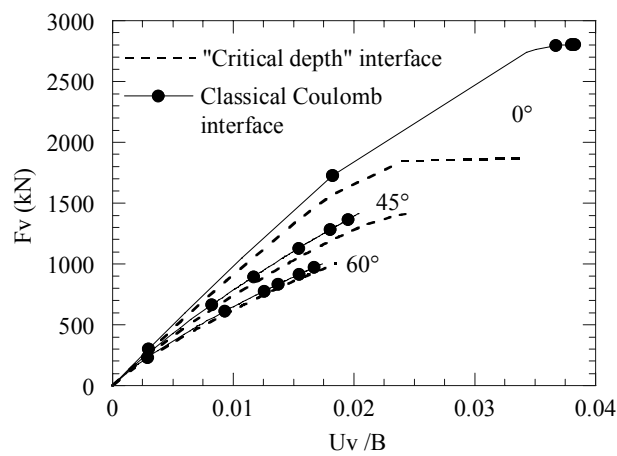
Figure 14 shows the influence of the interface modelling on the bearing capacity diagram of the pile in the coupled horizontal/vertical load space. It is assumed that the ultimate load corresponds to a vertical displacement $U = 0.1B$ (10% of the pile width). It can be observed that the interface condition affects the bearing capacity diagram. The consideration of a frictional interface leads to an important reduction of the bearing capacity in the vertical direction, in particular with the “Critical Depth” concept.

6. Conclusion

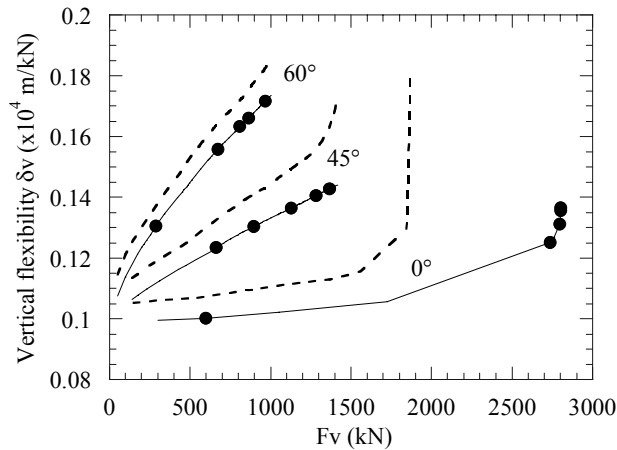
This paper included a three-dimensional finite element analysis of the influence of the interface on the response of piles to inclined loads. Both the classical and the “critical depth” concepts were investigated for the soil-pile interface. Analyses were conducted under the condition of small deformation, without large scale shearing and opening in the interface.

In these conditions, results of analyses show that the lateral response of piles is independent from both the loads inclination and the condition at the soil-pile interface. Consequently, the lateral component of the piles subjected to inclined loads can be treated by means of methods used for the design of piles under lateral loading.

Concerning the axial response of the pile, numerical simulations clearly show that this component is affected by both the load's inclination and the condition at the soil-pile interface.



(a) vertical displacement at the pile's head



(b) vertical flexibility of the pile

Figure 13. Influence of the "critical depth interface" on the pile response

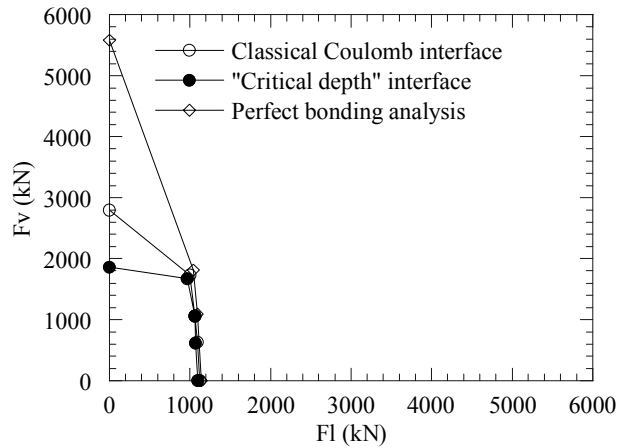


Figure 14. Bearing capacity of the pile (for a load inducing a head displacement $|U| = 0.1B$)

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