NUMERICAL MODELING OF VERTICAL PILES IN CLAY UNDER INCLINED COMPRESSION LOADING

MARTIN ACHMUS[1], KHALID ABDEL-RAHMAN[2]

ABSTRACT

For offshore structures vertical or nearly vertical driven piles are often used as foundation elements. In special cases, such piles experience not only vertical or axial, but also substantial horizontal loading. Current design practice is to consider axial and lateral loads separately and independently. In this paper the interaction between axial and lateral forces acting on vertical piles in cohesive soil is investigated by means of numerical modeling. A three-dimensional finite element model using the program ABAQUS was used. In this model the material behavior of the cohesive subsoil is described using an elasto-plastic constitutive model. The interactions between the pile and the surrounding soil are modeled thoroughly using contact elements based on slave-master concept. The behavior of the pile under combined axial and lateral loading is predicted in the scope of a parametric study for different pile geometries and different loading conditions. Finally, conclusions and recommendations are given concerning the design of piles under compressive combined loads.

Keywords: Offshore, piles, inclined loading, finite element method, Abaqus.

INTRODUCTION

In offshore technology vertical or nearly vertical driven piles are often used to found structures like e.g. platforms. Normally the axial loading of the pile is predominating. But in special cases, for instance for conductors used as auxiliary measure for drilling or for piles supporting offshore wind energy converters, the

[1] Prof. Dr.-Ing., Head of the Institute of Soil Mechanics, Foundation Engineering and Waterpower Engineering, Leibniz University of Hannover, Appelstr. 9A, D-30167 Hannover, Germany, Phone +49 511-762-4155; achmus@igbe.uni-hannover.de

[2] Dr.-Ing., Institute of Soil Mechanics, Foundation Engineering and Waterpower Engineering, Leibniz University of Hannover, Appelstr. 9A, D-30167 Hannover, Germany, Phone +49 511-762 2273; khalid@igbe.uni-hannover.de

vertical (axial) load is relatively small and the horizontal (lateral) load is thus substantial. The case considered here is that the pile is embedded in cohesive soil.

Current design practice involves separate analysis of the axial and lateral responses of piles and does not consider the effect of interaction between the different load directions. Several results of investigations concerning the behavior of piles subjected to combined axial and lateral loading (inclined loading) were reported in the literature, e. g. by Yoshimi (1964), Das et al. (1976), Chari & Meyerhof (1983), Ismael (1989), Sastry & Meyerhof (1990), Meyerhof (1995) and Amde et al. (1997).

In some investigations combined horizontal load and vertical compression load are concerned, in others oblique tensile loads are considered. From these investigations, it seems that the pile response to horizontal loading is only slightly affected by a vertical load, whereas horizontal loads significantly affect the vertical pile response. In this paper, the results of a numerical study on the behavior of vertical piles embedded in clay under prescribed inclined displacements are presented.

FINITE ELEMENT MODELING

For the investigation of the behavior of vertical piles under combined loading conditions a three-dimensional (3-D) numerical model was used. The finite element programme ABAQUS (Abaqus 2006) was applied. Solid concrete piles with an embedded length of 20.0 m were considered. Two different diameters D = 2.0 and D = 1.0 m were chosen in order to study the effect of pile geometry.

One of the most important issue in geotechnical numerical modeling is the simulation of the soil's stress-strain-behavior. An elasto-plastic material law with Mohr-Coulomb failure criterion was used to describe the behavior of normally consolidated clay.

An undrained shear strength (c_u) of 20 kPa was assumed at the ground surface increasing at a rate of 4 kPa/m with depth and the soil modulus (E) was assumed as 30.0 MPa at the soil surface increasing with a gradient of 1.0 MPa/m (Fig. 2, right). The undrained friction angle (ϕ_u) was assumed to be 12.0° and the Poisson's ratio (ν) was set to 0.40 for the numerical modeling. The material behavior of the piles was assumed to be linear elastic with the parameters $E = 3.0 \cdot 10^4$ MN/m^2 (Young's modulus) and $\nu = 0.20$ (Poisson's ratio) for concrete.

With these parameters the vertical bearing capacity of the piles can be calculated analytically. Assuming the ultimate shear stress to $\tau_{max} = \alpha \cdot c_u$ with an interface roughness factor of $\alpha = 0.5$, the shaft resistance (R_s) is

$$R_s = \pi D L \alpha c_u(\text{z=L/2}). \qquad (1)$$

Neglecting the influence of foundation depth, the following Equation applies for the base resistance (R_b):

$$R_b = 0.25 \pi D^2 N_c c_u(\text{z=L}) \qquad (2)$$

with $N_c = 9.0$ for $\phi_u = 12°$. In Table 1 the results for the two different pile diameters considered are given.

Pile diameter D in m	Shaft resistance R_s in kN	Base resistance R_b in kN	Total resistance R in kN	R_b/R_s
1.0	1885	707	2552	0.38
2.0	3770	2828	6598	0.75

Table 1: Ultimate vertical capacities of piles with L = 20 m.

Due to the symmetric loading condition only a half-cylinder representing the sub-soil and the pile could be considered. The discretized model area had a diameter of twelve times the pile diameter. The bottom boundary of the model was extended by six times the pile diameter below the base of the pile. With these model dimensions the calculated behavior of the pile is not influenced by the boundaries (Fig. 1).

3-d continuum elements (C3D6 & C3D8) were used for the soil as well as for the pile. The contact behavior in the boundary surface between pile and soil was modeled using slave-master-concept. In order to describe the frictional behavior between the pile and the surrounding soil, the shaft interface roughness factor (α) was taken as 0.5. This means that the maximum allowable shear stress was assumed to be equal to the half of the undrained shear strength of the clay ($\tau_{max} = \alpha \cdot c_u$, see Equation 1). For full mobilization of the frictional stresses a certain relative displacement (elastic slip) between the pile and the surrounding soil is necessary.

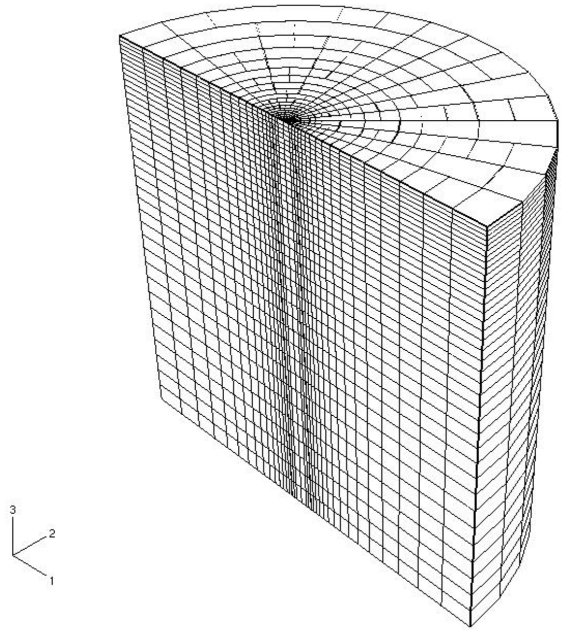

Figure 1: Finite element mesh.

The finite element modeling is executed stepwise. At first, for the generation of the initial stress state the whole model area is discretized using soil elements having a submerged unit weight of 10.0 kN/m^3 only. Subsequently, the pile is generated by replacing the soil elements located at the planned pile position by pile elements with a submerged unit weight of 15.0 kN/m^3 and activating the contact conditions between the pile and the soil. Finally, the vertical and the horizontal displacements are applied simultaneously and increased gradually until the required displacements are reached. This means that the directions of the displacement are prescribed. The piles were subjected to displacements with various inclinations ($\alpha = 0.0°$, 30.0°, 60.0°, 90.0°) measured from the horizontal direction (Fig. 2, left). Assuming $\alpha = 0.0°$ corresponds to pure horizontal displacement (and thus V = 0), whereas $\alpha = 90.0°$ corresponds to pure vertical displacement (H = 0).

The corresponding horizontal (H) and vertical (V) loads are calculated by integration of the horizontal and vertical bedding stresses (contact stresses) acting between the soil and the pile.

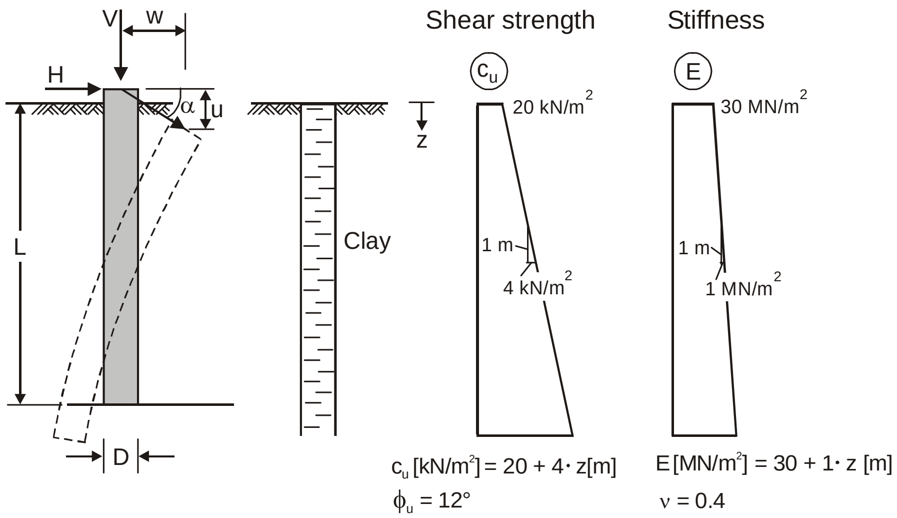

Figure 2: System, denominations (left) and soil parameters (right).

NUMERICAL MODELING RESULTS

For the problem concerned, the pile head displacements in the horizontal (w) and vertical (u) directions are of major interest. A comparison of the H-w- and V-u-curves (ref. to Fig. 2) can clearly show the effect of the vertical load on the horizontal load-deformation behavior and vice versa. Hence, such curves will be given in the following for different inclinations (α).

The pile head displacement in the vertical direction versus the applied axial force in shown in Figure 3. This plot illustrates that for a lower inclination angle, the vertical force required to displace a pile vertically is reduced. This means, the horizontal load has a unfavorable effect, since it leads to a softer behavior in the vertical direction.

The point at which all the curves in the Figure 3 (and also Figure 5) change their slope rapidly corresponds to the loading step where the incremental shaft resistance (skin friction) of the piles becomes zero, i.e. the ultimate shaft friction load (R_s) is reached. This means that the remaining stiffness and capacity is only due to the end bearing resistance (R_b) of the pile.

Up to this point there are nearly no deviations of the curves for different displacement inclinations. A substantial reason for the deviation beyond this points is that the horizontal bedding pressures induced by the horizontal loading affect the soil around the pile tip and thus decrease the end bearing resistance. As a result, the axial stiffness and the ultimate vertical pile capacity of the pile is decreased by additional horizontal loading.

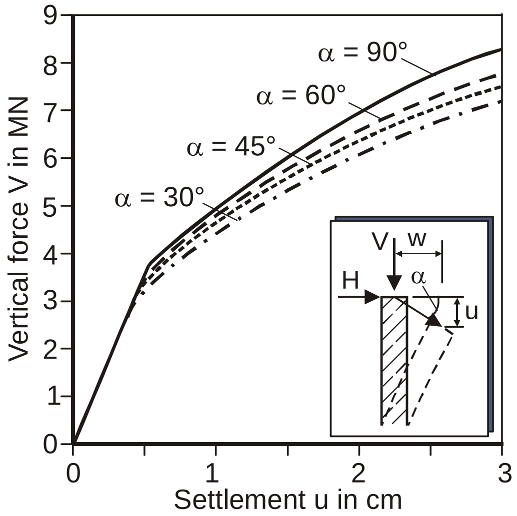

Figure 3: Vertical displacement at the pile top dependent on the vertical load (D=2.0m, L=20.0m).

The horizontal load deformation behavior for the pile with a diameter of 2 m is shown in Fig. 4. Due to these results, the horizontal displacement is nearly independent of the load inclination and thus independent of a vertical load acting together with the horizontal load. Similar results were found experimentally by Sastry & Meyerhof (1990), who carried out model tests with inclined compression loads.

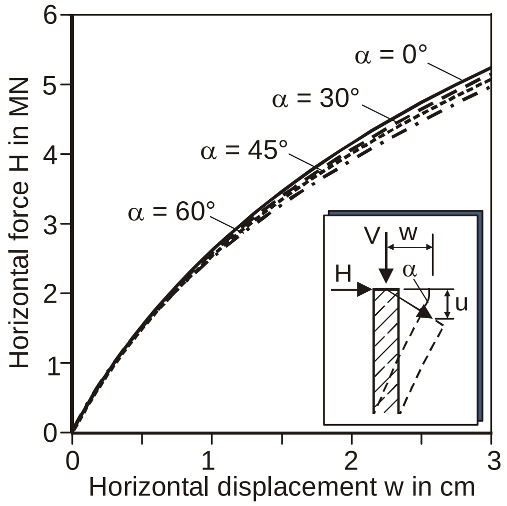

Figure 4: Horizontal displacement at the pile top dependent on the horizontal load (D=2.0m, L=20.0m).

Figs. 5 and 6 show the load-displacement curves for a pile with a diameter of 1 m. Similar results as for the case *D*=2 m are obtained. The horizontal load deformation behavior is again not affected, but the vertical stiffness and capacity are decreased by the presence of a horizontal load. Since for the smaller diameter *D*=1.0 m the load portion carried by the base resistance (R_b) is lower (see Table 1), the deviations of the curves for different displacement inclinations (see Figure 5) is slightly smaller than for *D*=2.0m (Figure 3).

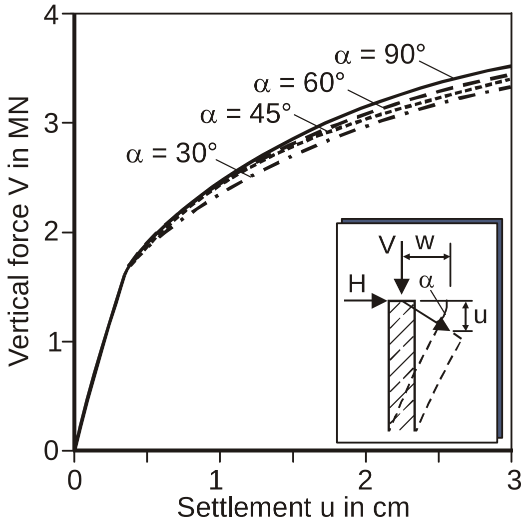

Figure 5: Vertical displacement at the pile top dependent on vertical load (D=1.0m, L=20.0m).

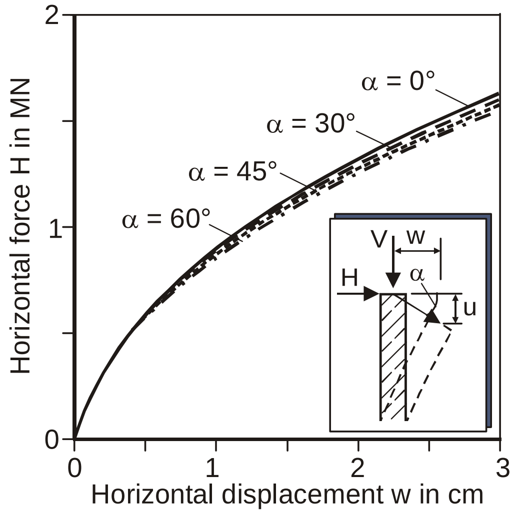

Figure 6: Horizontal displacement at the pile top dependent on the horizontal load (D=1.0m, L=20.0m).

CONCLUSIONS

According to the numerical calculation results, piles in soft cohesive soils under combined axial compression and horizontal load behave more unfavorably than purely axially loaded piles. A definite effect on the axial behavior of the pile is observed when the load inclination tends towards the horizontal direction. A reduction in the axial force required to displace the pile head vertically was observed for inclined loads. The horizontal pile stiffness is almost unaffected by a vertical compression load acting simultaneously.

For piles in soft clay loaded mainly in vertical direction the neglect of the effect of horizontal loads on the vertical stiffness and capacity might usually be suitable. But, if relatively large horizontal loads apply, the decrease of stiffness and also of pile capacity should be considered.

The authors also studied numerically the behavior of piles under inclined compression loading embedded in sand (Abdel-Rahman & Achmus 2005). It was found that for piles in sand the horizontal load has a favourable effect, since it leads to a stiffer behaviour in the vertical direction. The main reason for this is that in the upper part of the pile large horizontal bedding stresses act on the pile due to the horizontal load. A higher vertical stiffness and also a higher pile capacity is induced, because in sand the ultimate shear stress between pile and soil is dependent on the horizontal stress.

REFERENCES

Abaqus 2006. User’s manual, Version 6.5.

Abdel-Rahman, K. & Achmus, M. 2006. Numerical Modeling of the Combined Axial and Lateral Loading of Vertical Piles. *International Symposium on Frontiers in Offshore Geotechnics*, Perth, Australia, 575-581.

Amde, A.M., Chini, S.A. & Mafi, M. 1997. Model Study of H-piles subjected to Combined Loading. *Geotechnical and Geological Engineering*, Vol. 15, pp. 343-355.

Chari, T.R. & Meyerhof, G.G. 1983. Ultimate Capacity of Single Rigid Piles under Inclined Loads in Sand. *Canadian Geotechnical Journal*, Vol. 20, pp. 849-854.

Das, B.M., Seeley, G.R. & Raghu, D. 1976. Uplift Capacity of Model Piles under Oblique Loads. *Journal of the Geotechnical Engineering Division*, ASCE, 102(9), pp. 1009-1013.

Ismael, N.F. 1989. Field Tests on Bored Piles subject to Axial and Oblique Pull. *Journal of Geotechnical Engineering*, 115 (11), pp. 1588-1598.
Meyerhof, G.G. 1995. Behaviour of Pile Foundations under Special Loading Conditions. 1994 R.M. Hardy Keynote Address. *Canadian Geotechnical Journal*, Vol. 32, pp. 204-222.
Sastry, V.V.R.N. & Meyerhof, G.G. 1990. Behavior of Flexible Piles under Inclined Loads. *Canadian Geotechnical Journal*, 27(1), pp. 19-28.
Shahrour, I, & Meimon, Y. 1991. Analysis of Behavior of Offshore Piles under Inclined Loads. *International Conference on Deep Foundations*, pp. 227-284.
Yoshimi, Y. 1964. Piles in Cohesionless Soil subject to Oblique Pull. *Journal of the Soil Mechanics and Foundations Division*, ASCE, 90(6), pp. 11-24.