XIII ICSMFE, 1994. New Delhi, India / XIII CIMSTF, 1994. New Delhi, Inde

CYCLIC LOADING RESPONSE OF MODEL ANCHOR PILES IN CLAY

REPONSE DYNAMIQUE DES PIEUX MODELES D'ANCRAGE EN ARGILE

***J.O. Steensen-Bach*[1] *G. Bouckovalas*[2] *A. Anagnostopoulos*[2] *J.S. Steenfelt*[1]**

[1]Danish Geotechnical Institute, Copenhagen, Denmark
[2]National Technical University of Athens, Athens, Greece

SYNOPSIS. As a part of a research program on the design of anchor piles for Tension Leg Platforms 5 monotonic, 4 cyclic and 4 post-cyclic monotonic pile load tests have been performed using model piles in clay. The aim of the tests was

- to estimate the static pullout capacity and stiffness of the model piles at loading rates similar to those imposed during cyclic loading,
- to provide data on permanent displacement accumulation and incremental collapse during sustained cyclic loading and,
- to estimate the degradation of static pullout stiffness and capacity due to cyclic loading

The effect of cyclic loading on the axial stiffness and the pull-out capacity of the model piles is assessed from comparison of the static test results obtained before and immediately after cyclic loading.

INTRODUCTION

The static and cyclic response of piles in clay under axial compressive loading has been the subject of extensive experimental investigation in the past. In contrast the response of piles in tension (anchor piles) has received much less attention. However, relevant research has clearly been intensified in the last decade, in connection with the design of the first tension leg platforms (TLPs). The current design practice (A.P.I. 1989, Focht & O'Neill 1985) for monotonic and cyclic loading does not distinguish between piles in tension and piles in compression. This is based on the general conclusion derived from a number of investigations (i.e. Kraft et al 1981, O'Neill et al 1982, Karlsrud and Haugen 1983, Hegedus & Khosla 1984, Jaime et al 1989) that a gross similarity exists between the two different types of pile, with respect to the ultimate shaft resistance and the load-deformation response for monotonic loading and unloading. However, this conclusion oversees differences that may rise close to failure, concerning the displacements of the pile head (i.e. O'Neill et al 1981, Jaime et al 1989) and the failure mechanism (Kulhawy 1985, Chatopadyay & Pise 1986). Furthermore, it is based mostly on experimental data for monotonic loading, since the available literature for cyclic loading is relatively limited and focuses mainly upon piles in compression. In the following, data are presented from monotonic and cyclic pull-out tests on anchor piles in clay, performed as a part of an experimental and analytical research on the design of anchor pile foundations for TLPs (A.D.K. 1991). The tests included a number of cyclic loading tests, as well as monotonic (static) tests, performed before and immediately after the cyclic tests in order to assess the pull-out capacity and its degradation due to cyclic loading.The paper focuses upon the pre- and post-cyclic monotonic tests, used to assess the effect of cyclic loading on the axial stiffness and the pull-out capacity of the model piles.

MODEL TEST SET-UP AND PROCEDURES

Model tests were carried out under 1g gravity, on model piles, jacked into two normally consolidated clay cakes. After a 24 hour period the submerged piles were subjected to either strain controlled monotonic tensile loading (static test) or stress controlled cyclic tensile loading. The model piles, shown in Fig.1, were designed based on the modular model pile design of Francescon (1983). In this concept the aluminium pile consists of a top plug for over-all load transfer, a tip plug closing the hollow pile and five sections, each of 80 mm length, 3 mm wall thickness and 19 mm external diameter connected by axial load cells. The measuring unit of the axial load cells consists of strain gauges positioned on a transition part connecting any two sections, with wall thickness of 1.0 mm, placed inside the pile. The clay cakes, A and B (Table 1) were unloaded prior to pile installation. The unloading of the clay cakes left a negative pore-water pressure in the cakes corresponding to the total unloading stress. To monitor this change the shear strength of the clay cake was determined by hand vane tests before and after each model test, performed at depths of 100, 200, 300 and 400 mm from the free surface. The results of the field vane test measurements are summarized in Figure 2. Before pile installation, the top of the clay cake is leveled using as a guide the consolidometer top and leaving a clay cake of 500 mm height and a diameter of 530 mm. The piles were installed using a constant rate of penetration. This ensured that identical penetration depths (= 400 mm) were obtained in all tests, and that similar soil distortions may be assumed.

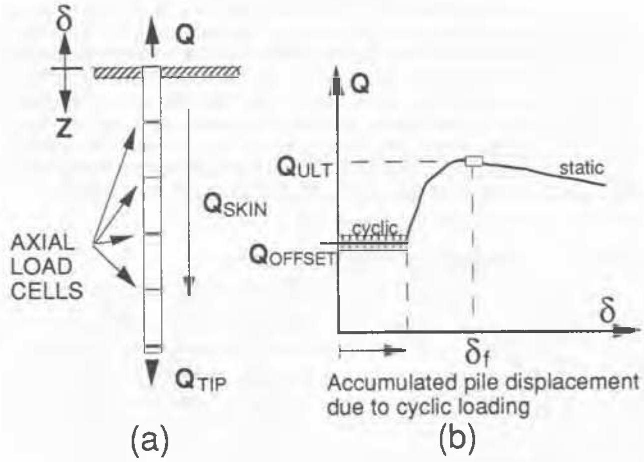

Fig.1. (a) Modular design of model pile (b) Typical load-deformation curve for post-cycling monotonic pull-out test

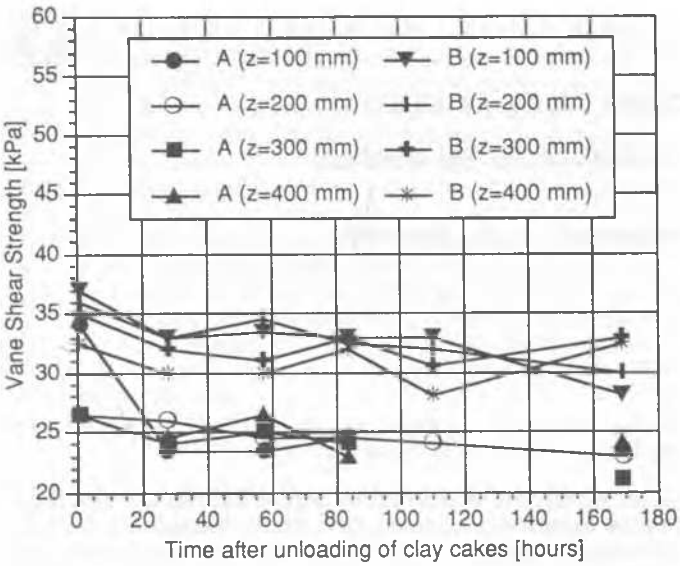

Fig.2. Variation with time and depth of vane shear strength in clay cakes A and B

Pile deflection in the horizontal plane at soil surface level was reduced to less than 0.1 mm during installation. After installation the free water level was raised to a level 5 mm above the clay surface. During installation, the soil around the pile is disturbed to a radial distance of about two pile radii from the pile axis (e.g. Randolph et al 1979) while radial displacements of the soil occur within a maximum radial distance of five pile radii (Steenfelt et al 1981, Francescon 1983). Keeping this in mind the model pile was installed at a minimum distance of ten pile radii from the consolidometer wall, and at least twenty pile radii from previous installation points. To ensure dissipation of installation-induced excess pore pressures in the clay cakes, a rest period of 24 hours was allowed after pile installation.

Table 1. Properties of Nivaa Clay Cakes

Clay Cake	A	B
Liquid Limit (%)	35	35
Plastic Limit (%)	15	15
Grain unit weight (kN/m³)	27.3	27.3
Initial moisture content (%)	62.0	61.8
Final moisture content (%)	28.9	27.1
Preconsolidation stress , σ (kPa)	222	260
Vane shear strength, c_u (kPa)	34.0 *)	37.0 *)
Strength ratio c_u/σ	0.153	0.142

*) at 100 mm below consolidometer top

MODEL TEST PROGRAM

Following installation and regeneration (rest) period, model piles were subjected to three different types of static and cyclic tension tests (cf Table 2). (I) Rapid Static Loading Tests. To estimate the static pull-out capacity of the model piles for loading rates comparable to the one imposed during cyclic loading, five identical tests (Tests 1a, 2a, 3a, 4a and 9a) were performed at different times after clay cake unloading in two different clay cakes (A and B). Tests were performed with displacement control and an approximate time to failure of 8 to 13 sec's. The ultimate loads in tests 1a and 2a are denoted F1 and F2. (II) Cyclic Loading Tests. To provide data on permanent strain accumulation for various tensile cyclic load amplitudes, $(F_p)_{ampl}$, three tests (Tests 5a, 6a, 7a) with constant amplitude and one test with gradually increasing load amplitude (Test 8a) were performed. The cyclic loading was applied after application of a static, tensile off-set value, $(F_p)_{offset}$, corresponding to 0.5 times ultimate static load (Table 2). Cyclic loading was done at a rate of 6 cycles/min. (III) Post-Cycling Static Tests. To obtain data on the short-term degradation of static pull-out capacity caused by sustained cyclic loading, four tests were performed (Test No 5b, 6b, 7b and 8b) following immediately (no rest period) after each of the cyclic tests, with displacement control and an approximate time to failure of about 4 to 13 sec's.

Table 2. Model Pile Test Program

Test No	Clay cake	Total time [h]	Static Offset Load	Cyclic Load Amplitude²	No of cycles	Test type
1a	A	27	0	0	0	I
2a	B	27	0	0	0	I
3a	A	110	0	0	0	I
4a	B	105	0	0	0	I
5a	A	57	0.48 F1	0.16 F1	1006	II
5b	A	57	0	0	0	III
6a	A	105	0.48 FI	0.33 F1	39¹	II
6b	A	105	0	0	0	III
7a	B	80	0.47 F1	0.25 F2	50¹	II
7b	B	80	0	0	0	III
8a-1 8a-2 8a-3 8a-4	B	55	0.47 F2 0.48 F2 0.49 F2 0.50 F2	0.11 F2 0.22 F2 0.28 F2 0.34 F2	200 200 200 165¹	II
8b	B	55	0	0	0	III
9a	B	166	0	0	0	I

¹) Test stopped on displacement criterium
²) F1= 628 N (test 1a), F2= 799 N (test 2a)
I) Rapid tensile test at constant strain rate
II) Cyclic stress-controlled tensile test
III) Post-cycling tensile test at constant strain rate

Cyclic tests were terminated either after 1000 cycles or when the accumulated pile displacement exceeds the displacement at failure in rapid static tests (Type I), i.e. > 5 mm.

INTERPRETATION OF RAPID STATIC TESTS

The rapid, static tests allow elucidation of the basic static response of the model piles. Furthermore, they provide a framework for evaluation of the effect of cyclic loading on the post-cyclic static behaviour of the piles. Figure 3 shows internal pile load distributions for test 1a measured immediately after pile installation, after 24 hours of regeneration, at 50% of the static pull-out capacity, Q=0.50 Q(ult), and at failure Q=Q(ult). It is observed that small residual loads remain after installation of the pile, which are positive (tensile) in the upper portion of the pile and negative (compressive) in the lower portion. During regeneration, these loads become gradually positive (tensile) all over the pile, a possible effect of heave following unloading of the clay cake. The maximum tensile load is measured in the lowest section of the pile, 8 mm above the tip, and exceeds half of the load measured in this section when failure occurs, and it is about equal to the (estimated) ultimate tip suction, Q(tip). The internal load distribution at failure, Q=Q(ult), and at the intermediate loading stage, Q=0.50 Q(ult) can be fitted by a linear relationship, which is typical of more or less rigid piles embedded into uniform soils. Based upon this observation information on the ultimate pull-out capacity of the pile, the tip suction Q(tip) at failure (from linear extrapolation of the test measurements to the depth of 400 mm) and the average shaft friction at failure $f_s = [Q(ult) - Q(tip)]/(\pi\ D\ L)$ can be obtained from the measured internal load distribution at failure. Figure 4a shows the variation of Q(ult) with time after unloading, measured in clay cakes A and B. The values of Q(ult) in clay cake B are consistently larger than the ones in clay cake A by about 17%, as expected for the larger consolidation pressure applied in this clay cake. Because of this difference the data in Fig.4a have been normalized with respect to the ultimate pile capacity at 27 hours after unloading of the clay cakes Q(ult,o) = 0.65 kN and 0.80 kN for clay cakes A and B, respectively.

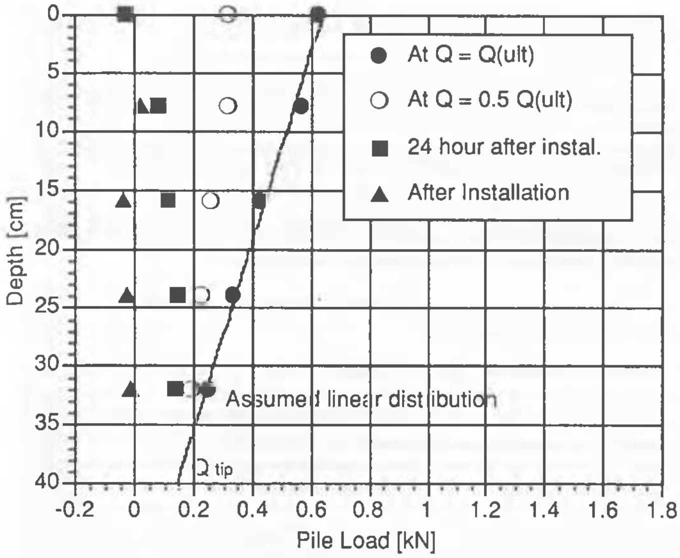

Fig.3. Internal load distribution at different stages of static test 1a

In this way, both sets of data form a unique relationship indicating a steady degradation of Q(ult) with time at a rate of 0.002 kN/hour. The causes of this degradation are explored with the aid of Figures 4a and 4b which show the variation with time of the shaft friction parameter $\alpha = f_s/c_u$ and the normalized tip suction $Q(tip)/Ac_u$ (A is the cross sectional area of the pile and c_u is the undrained shear strength of the clay cakes). These figures reveal that the degradation of Q(ult) is mostly related to the degradation of the skin friction, since the ultimate tip suction remains practically constant with time after unloading of the clay cakes. Thus, the degradation of ultimate pile capacity may be related directly to the time reduction in skin friction, as the undrained shear strength of the clay cake shows no significant variation with time. The exact causes of this reduction is not known with confidence. There is enough evidence however, to suggest that it must be related somehow to the dissipation of negative pore pressures developed in the clay cakes after unloading, and the associated gradual change of the clay from normally to slightly overconsolidated state.

STATIC PILE RESPONSE AFTER CYCLING

All post cyclic static tests were performed immediately after completion of cyclic loading (no rest period), at rapid loading rates similar to the ones which were adopted for the initial static tests. Thus, any possible effects of cyclic loading may be determined by comparing directly the results obtained from the post cyclic and the initial static tests at the same clay cake. Care should only be taken to account for the effects of elapsed time after unloading of the clay cakes, considering that the post cyclic and the initial tests were performed at different times. To this extent, post cyclic static test results are compared to "respective" (with regard to elapsed time) initial static test results estimated from the relationships shown in Figure 4. The effect of cyclic loading on ultimate pull-out capacity is shown in Figures 5a and 5b, where the ratio of post-cyclic to initial ultimate load [Q(ult,p)/Q(ult)], skin friction coefficient [Q(s,p)/Q(s)] and tip suction [Q(tip,p)/Q(tip)] are plotted against the cyclic displacement amplitude (δ_{cvc}) at the final stages of the cyclic pile load tests. According to the experimental data cyclic loading with displacement amplitude larger than 0.10 to 0.20 mm, or about 0.5% to 1.0% of the pile diameter, causes degradation of the ultimate pile capacity which is evenly attributed to the simultaneous degradation of the skin friction and the tip suction. The maximum amount of ultimate capacity degradation is 20 % which is obtained for cyclic displacement amplitudes which range between 0.6 and 0.7 mm, or 3.0 to 3.7 % of the pile diameter. At the same level of cyclic displacement amplitude, the degradation of skin friction and tip suction amount 15±5 % and 23±3 % respectively. The rate of ultimate pile capacity degradation with increasing cyclic displacement

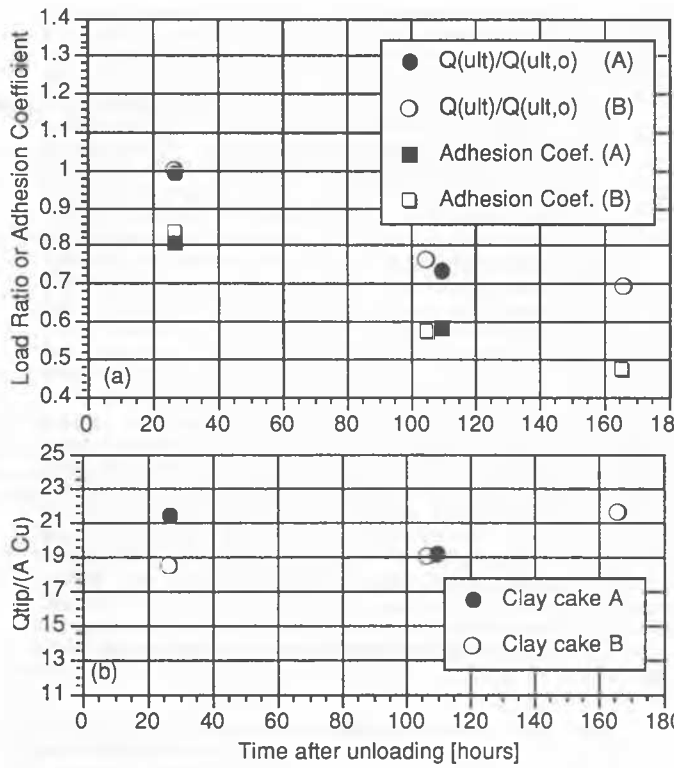

Fig.4. Degradation of ultimate pile capacity with time after unloading of the clay cakes

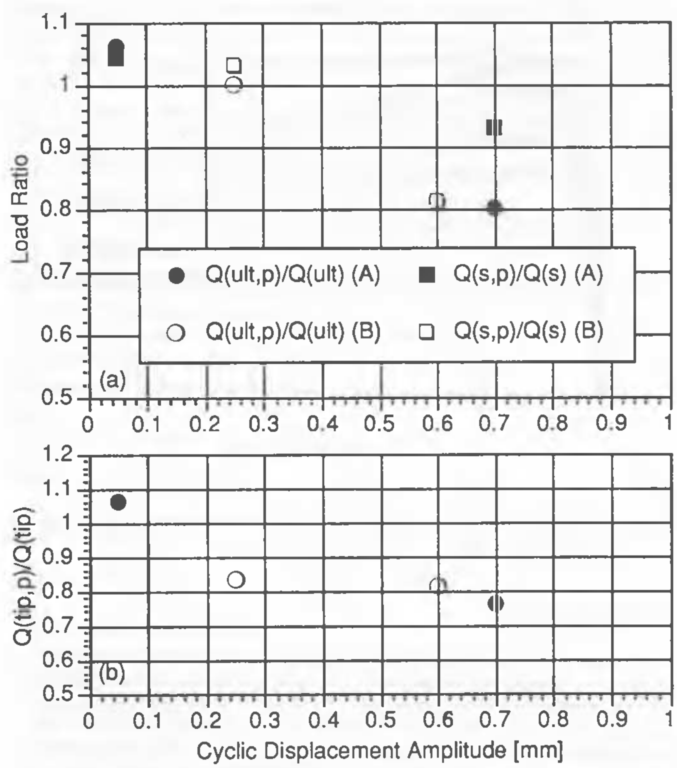

Fig.5. Effect of cyclic displacement amplitude on post-cycling static pull-out capactity

amplitude appears to decrease gradually; this trend is more evident for the tip suction which tends to stabilize quickly at about 70 % to 75 % of its initial value. The trends observed in Figure 5 are consistent with previous findings, mainly for piles in compression (Matlock et al. 1982), Doyle and Pelletier 1985) but also for piles in tension (Karlsrud and Haugen , 1983), which indicates that one-way cyclic loading may cause a 10-20 % reduction of the ultimate pile capacity. This reduction applies to both components of pull-out capacity, skin friction and tip suction, and is primarily a function of the cyclic displacement amplitude applied to the pile. It is important to note that a similar presentation of the experimental data with reference to the normalized cyclic loading amplitude (Q_{cyc}/Q_{ULT}), not shown here, considerably increased the scatter of the data, as well as the uncertainty regarding any observed trends. The load-deformation curves from the initial and the post cyclic static pull-out tests performed in clay cakes A and B are compared in Figures 6a and 6b respectively. A common trend identified in both figures is that the post cyclic static pull-out tests exhibit a more "brittle" response as compared to the initial tests, characterized by a larger initial stiffness, an abrupt yield and a smaller deformation at failure. The effect of cyclic loading on the static load-deformation response may be described quantitatively by the ratios of the post cyclic to initial ratios of stiffness at 50 % of the failure load, and pile head displacement at failure [$\delta(f,p)/\delta(f)$]. The post cyclic to initial stiffness ratio obtained from the tests ranges between 0.84 and 1.63, with an average value of 1.29, while the ratio of post cyclic to initial displacement at failure ranges between 0.54 and 1.17, with an average value of 0.71. No clear relationship seems to exist between the above values of the post cyclic to initial load and displacement ratios with the load or the displacement amplitude applied in the cyclic tests.

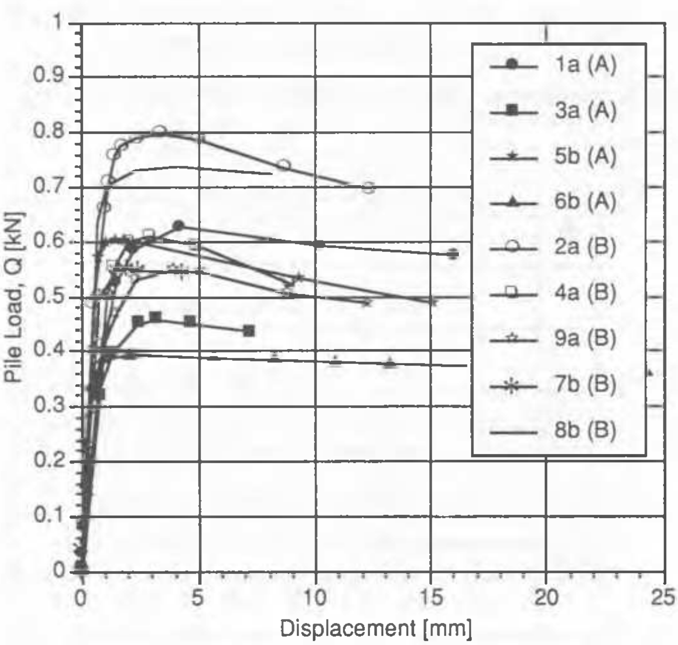

Fig.6. Effects of cyclic loading on load-displacement response in static pull-out tests

CONCLUSIONS

In summary, the main conclusions derived are: (a) One way cyclic loading in tension may cause short term degradation of the ultimate pull-out capacity and its components, the shaft resistance and the tip suction, by as much as 20%-30% relative to the initial pre-cyclic capacity. (b) The amount of degradation appears to be a main function of the maximum cyclic displacement of the pile head during cyclic loading. The minimum cyclic displacement amplitude required to trigger ultimate capacity degradation is equal to 0.10 -0.20 mm or about 5%-10% of the pile diameter.(c) Post-cyclic monotonic pull-out tests exhibited up to 63 % larger initial stiffness and up to 46 % smaller displacement at failure compared to initial pre-cyclic tests. This effect of cyclic loading appears to be independent from the static and cyclic loads or displacements applied during cyclic loading. In stating the above conclusions, it is acknowledged that the number of tests is relatively small and, combined with the well known difficulties in performing the tests, may justify some reservations regarding the quantitative description of the cyclic loading effects. Further field and laboratory testing of well instrumented piles is considered necessary in order to evaluate the full extent of the effect of cyclic loading and its practical implications to the design of anchor piles.

ACKNOWLEDGEMENT

The work presented in this paper is a part of a research project Foundation Design Under Cyclic Loading for Tension Leg Platforms, European Community Project No. TH 03314 HE in the Hydrocarbon Sector. The project was carried out as a joint industri project between Aronis-Drettas Karlaftis Consulting Engineers (ADK), Greece, EOS Hellas Ltd, Greece and the Danish Geotechnical Institute (DGI), Denmark with National Technical University of Athens (NTUA) acting as consultants. Model tests were carried out at DGI. The presented analysis of the tests were carried out at NTUA.

REFERENCES

A.D.K. (1991). Foundation Design Under Cyclic Loading for Tension Leg Platforms *Research Report, Project No. TH 03314 HE, Dir.General for Energy, Comm. of the Europ. Communities*

American Petroleum Institute (1989). Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms. *API Recommended Practice 2A,* 18 edition

Chatopadyay, B.C.& Pise, P.J. (1986). Uplift Capacity of Piles in Sand. *JGED, ASCE,* Vol. 112, No.9, pp.888-904

Doyle, E.H. and Pelletier, J.H. (1985). Behaviour of Large Scale Piles in Silty Clay.*Proc. of XI Inter. Conf. on Soil Mech. and Found. Eng.*, San Francisco, pp.1595-1598

Focht, J.A.& O'Neill, M.W. (1985). Piles and other Deep Foundations. *State of the Art Report, XI Inter. Conf. on Soil Mech. and Found.Eng.* , San Francisco, pp.187-209

Francescon, M. (1983). Model Pile Tests in Clay - Stresses and Displacements due to Installation and Axial Loading. *PhD-Thesis,* Cambridge University

Hegedus, E. & Khosla, V.K. (1984). Pull-out Resistance of H Piles. *JGDE, ASCE,* Vol.110, No.9, pp.1274-1290

Jaime, P. & Romo, M.P. (1989). Static Tests on Friction Piles in Mexico Clay. *Proc. XII Inter. Conf. on Soil Mech. and Found. Eng.,* Rio de Janeiro, pp.1141-1146

Karlsrud, K. & Haugen, T. (1983). Cyclic Loading of Piles And Pile Anchors - Field Model Tests. *Norwegian Geotechnical Institute* (final) Report No. 40010-28

Kraft, L.M. Cox, W.R. & Verner, E.A. (1981). Pile Load Tests: Cyclic Loads and Varying Load Rates. *JGDE, ASCE,* Vol.107, No.GT1, pp.1-19

Kulhawy, F.H. (1985). Drained Uplift Capacity of Drilled Shafts. *Proc. XiI Inter. Conf. on Soil Mech. and Found.Eng.,* San Francisco, pp.1549-1552

Mattlock, H. Bogard, D. and Cheang, L. (1982). A Laboratory Study of Axially Loaded Piles and Pile Groups including Pore Pressure Measurements. *BOSS'82,*, pp.105-121

O'Neill, M.W. Hawkins, R.A. and Mahar, L.J. (1982). Load Transfer Mechanisms in Pilesand Pile Groups. *JGDE, ASCE,* Vol.108, No.GT12, pp.1605-1623

Randolph, M.F. Steenfelt, J.S. and Wroth, C.P. (1979). The Effect of Pile Type on Design Parameters for Driven Piles. *Proc. VII Europ. Conf. on Soil Mech. and Found.Eng.*,pp.107-114

Steenfelt, J.S. Randolph, M.F. and Wroth, C.P. (1981). Instrumented Model Piles Jacked into Clay. *Proc. X Inter. Conf. on Soil Mech. and Found.Eng.*, Stockholm, Vol.2, pp.857-864