Geotechnical Engineering, Vol. 21, 1990

MODEL PILES EMBEDDED IN SUBMERGED SAND AND SUBJECTED TO STATIC AND CYCLIC LATERAL LOADINGS

S.N. Abduljauwad[1], G.J. Al-Sulaimani[2] and I.A. Basunbul[3]

SYNOPSIS

The effects of a number of variables on pile performance can be studied readily in the laboratory on model piles, thereby avoiding the effort, expense and time involved in full scale testing. This study shows that testing small scale model piles can be used to understand the performance of laterally loaded piles embedded in sandy soil. The experimental program consisted of carrying out investigations on model piles embedded in saturated sand under various loading conditions (static vs cyclic). The static and cyclic loadings were achieved by means of a specially designed loading actuater, where the cyclic load represents the wave action on an offshore structure. The experimental load deflection curves were developed from the reduced data at different depths for static and cyclic loading. Numerical solutions utilizing the experimental p-y and semi-em- pirical curves were developed. A comparison of experimental bending moment and deflection along pile length was made with the numerical solution using the semi-empirical as well as experimental p-y curves. Experimental results agree reasonably with the numerical solution, indicating the validity of model study in predicting the behaviour of laterally loaded pile.

INTRODUCTION

The continuous search for petroleum offshore has led to the construction of several hundreds of offshore platforms worldwide. These platforms are usually supported on pile foundations. Lateral loads developed by wind and wave actions are the most critical factor required in the design of such structures. The problem of piles subjected to a lateral loading is one of a class of problems concerned with the interaction of soils and structures.

The techniques currently available for the analysis and design of laterally loaded piles are based on full scale testing in the field. Based on these tests, design

[1,2,3] Department of Civil Engineering, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia

bending moment, shear force, deflection and slope along the pile length are obtained (Kim, et al. 1979; Ting 1987; Brown, et al. 1988). Also, a solution of the laterally loaded piles can be obtained by correlating the results from the full scale tests with theoretical equations to obtain resistance-deflection (p-y) curves which can be combined with numerical procedures for complete design of the piles (American Petroleum Institute, 1982).

These full scale tests involve a lot of effort, expense and time. However, this cumbersome procedure can be substituted by small scale testing of piles in the laboratory simulating field conditions. The study of small scale piles described here involves development of an experimental setup and loading conditions in the laboratory which simulate the behaviour of laterally loaded piles in an offshore structure.

EXPERIMENTAL PROGRAM

The behavior of a laterally loaded single pile was studied in the laboratory using small scale piles. The test program consisted of studying small scale piles embedded in saturated sand and subjected to static and cyclic lateral loadings. The small piles were cut from steel pipe with diameter D = 28.8 mm and wall thickness length t = 1.5 mm to 775 mm length. The steel pipe was made out of hot rolled steel with an elastic modulus of 223 GPa and yield strength of 340

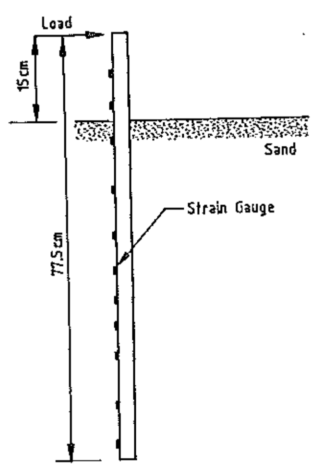

Fig. 1 Sketch of Model Piles Shows the Distribution of Strain Gauges.

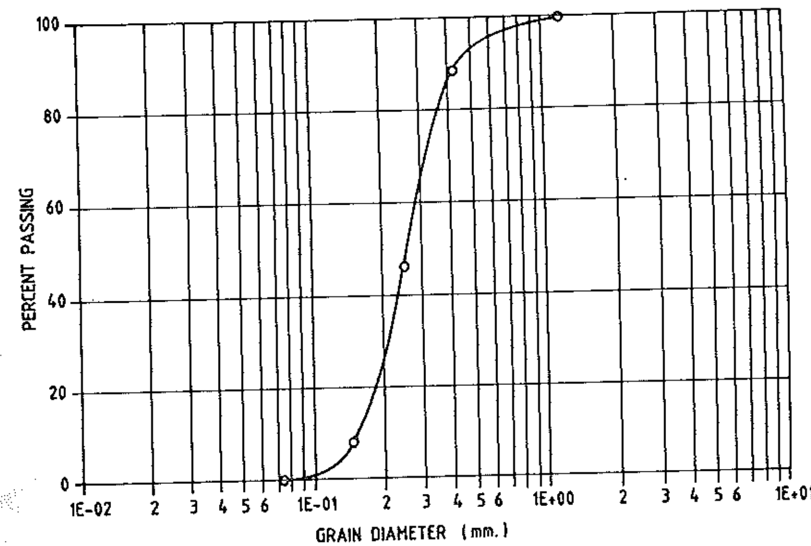

Fig. 2 Grain Size Distribution Curve for Sand

MPa. Each pile was instrumented with eleven strain gauges placed along its length as shown in Fig. 1. The strain gauges used were FLA-10-11 type having a gauge length of 10 mm and gauge factor of 2.12. A catalyst solution was applied to the back of the gauge and then a small quantity of M200 bond glue was applied. The gauge was placed by hand in the required position with sufficient pressure until the strain gauge adhered to the pile surface. These strain gauges need to be protected against friction of sand and entry of water, for this purpose epoxy sealant was used. Two portions of resin was mixed thoroughly with one portion of hardener for 5 minutes until a paste of uniform color and consistency was obtained. This resulting paste was applied to the strain gauges carefully and left to dry for about twelve hours. After drying, the pile was kept in a system of sand and water to check the performance of the coating. The fine sand used had a grain size distribution curve as shown in Fig. 2. The sand had 80 percent of grains between 0.15 mm and 0.42 mm. The specific gravity, effective size, uniformity coefficient and coefficient of curvature were 2.67, 0.15 mm, 1.73 and 1.03 respectively. Results from direct shear testing indicated the sand had an angle of internal friction of 34° with a dry density of 1700 kg/m^3.

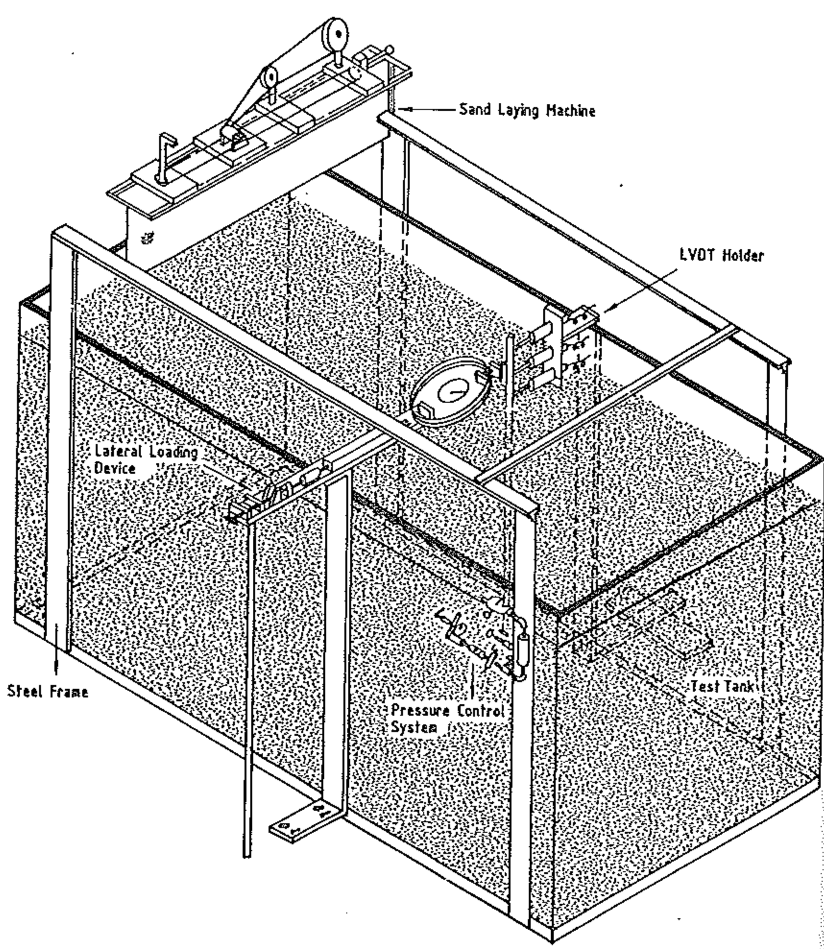

Fig. 3 Three Dimensional View of Test Setup

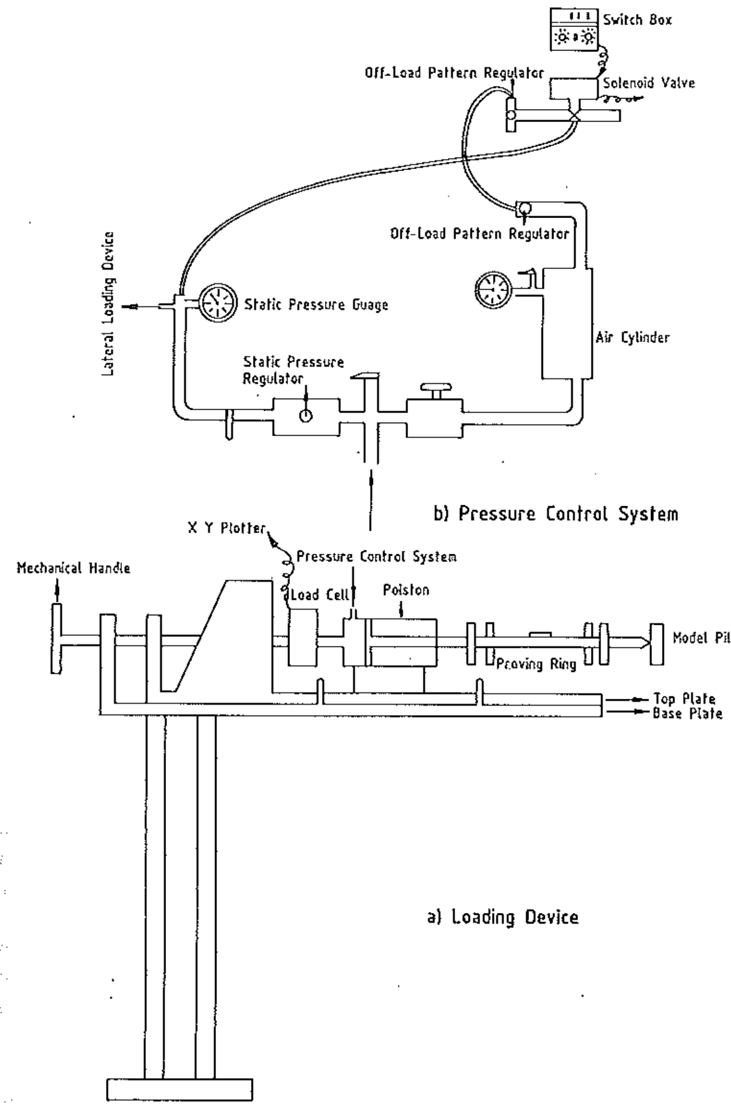

Fig. 4 Line Diagram of Loading Device & Pressure Control System

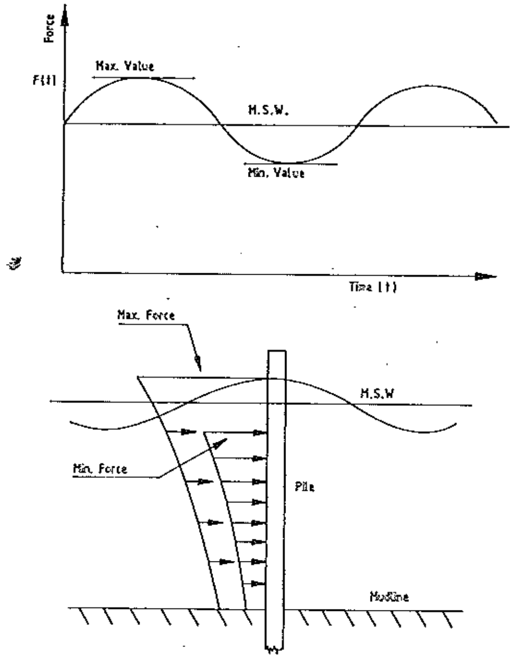

Fig. 5 Transient Wave Loading on Vertical Cylinder Piles

The experimental program was performed using a test tank (see Fig. 3) of 1200 mm by 800 mm and 600 mm height made of plexiglass sheets and reinforced horizontally and vertically with steel channels. Dry sand was laid in the tank using a sand-laying system which was specially developed as part of this research to achieve a uniform relative density of 85% of the sand. The sand was then saturated by means of plastic hoses connected to the bottom of the test tank and to a water tank. Water was introduced to the test tank very slowly to avoid boiling condition in the sand. Details of this system are given in the work by Shameem (1988).

Both static and cyclic lateral loadings were applied to the top of the pile using air pressure in a specially developed loading system shown in Fig. 4. The system comprises of a pressure regulator which controls the magnitude of the

static loading or the minimum sustained load of the cyclic loading. A solenoid valve is attached to an air cylinder to apply the peak cyclic load. A typical transient wave loading which this system is capable of simulating is illustrated in Fig. 5

The load and the corresponding deflections at three points at the top portion of the pile were measured using linear variable displacement transducers (LVDT) and recorded using an automatic data acquisition system. Also, at each load level, readings of strain from the gauges along the pile length were recorded. Fig. 3 and Plate 1 show the complete test setup of the laterally loaded small scale piles.

TEST RESULTS AND DISCUSSION

Static loading

As part of this research the behavior of a small scale pile embedded in sand and subjected to a lateral static loading under submerged condition was studied.

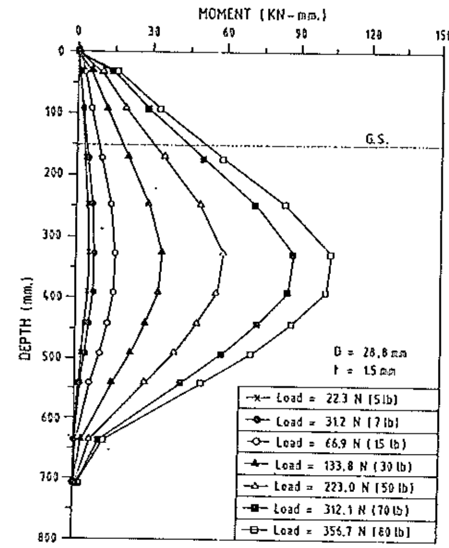

Fig. 6 Bending Moment Veriation along Pile Length for Static Loading

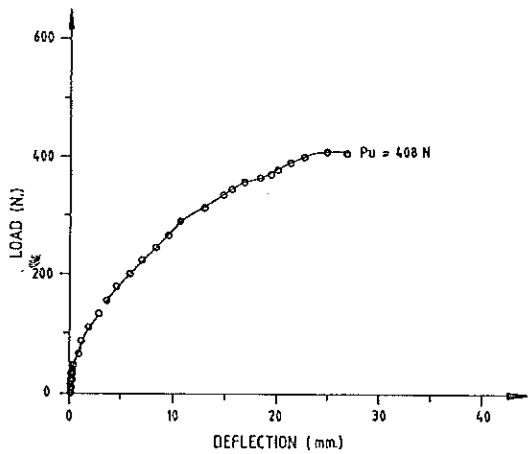

Fig. 7 Load-Deflection Curve for the Pile Top

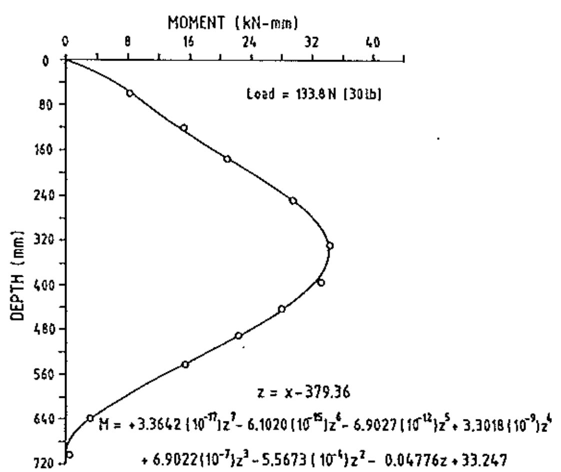

Fig. 8 Seven Degree Polynomial Best Fit for the Moment Data at a Load of 133.8 N

The load was applied in small increments until excessive pile head deflection occurred (deflection which exceeds the pile diameter).

From the strain gauges readings at a certain load level, bending moment along the pile length was computed using simple beam theory. The moment was calculated using the following equation

$$M = \varepsilon \frac{EI}{y}$$

where ε, E, I and y represent the measured strain, modulus of elasticity of steel, moment of inertia of pile section and distance from centroid to extreme fiber respectively. The variation of bending moment along the pile length at different load levels is shown in Fig. 6. The maximum bending moment occurs at a depth of 200 mm below the top of the sand level, it occurs at that depth and not at the surface because of the combining effects of moment, shear and soil resistance. The load deflection curve for the top of the pile is depicted in Fig. 7.

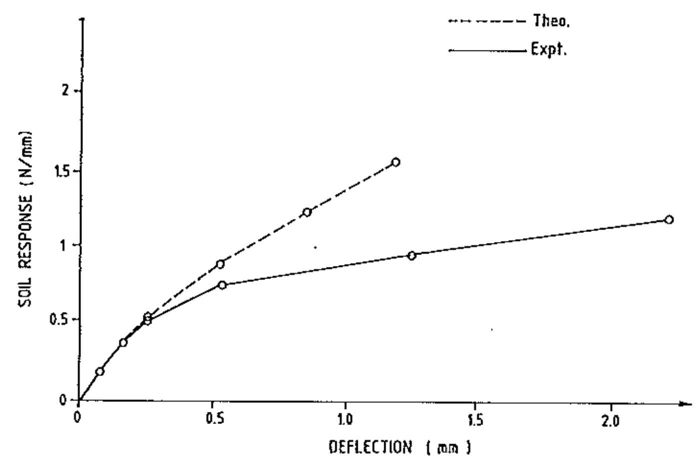

Fig. 9 Comparison of Theoretical and Experimental p-y Curves at a Depth of 291 mm

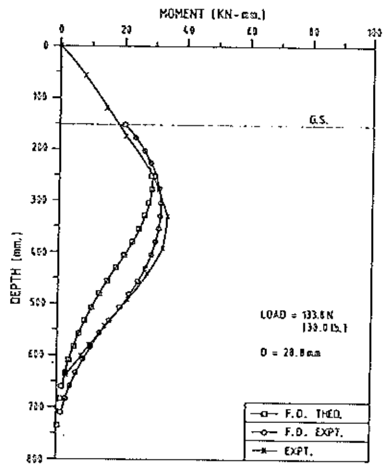

Fig. 10 Comparison of Experimental Moment with Numerical Moments

A seven degree polynomial similar to the one used by Ting (1987) was developed to best fit the moment data (Abduljauwad, et al., 1990). Fig. 8 shows the best moment fit which was obtained by the seven degree polynomial at a load level of 133.8 N under submerged condition. The moment expression was differentiated twice to get soil resistance, P, and integrated twice to obtain pile deflection, y, along the pile length Fig. 9 shows a comparison between the experimental p-y curves and the semi-empirical p-y curves which were developed by Reese, et al. (1974). The difference between the p-y curves obtained from the model test and the Reese p-y curves was expected due to the differences in pile size, soil type, density and environmental conditions. This is because the Reese p-y curves were derived from a full scale field test conducted on Mustang Island. The developed experimental p-y curves as well as the semi-empirical p-y curves obtained by Reese, et al. were used separately in a FORTRAN computer program to obtain bending moment along the pile length. The program is based on non-linear Winkler analysis using the finite difference (F.D.) method. Comparison of the experimental bending moment with moments obtained by computer program with experimental and semi-empirical p-y curves at a load level of 133.8 N is shown in Fig. 10. Good agreement is noted between the experimental results (EXPT) and the numerical solution using the experimental

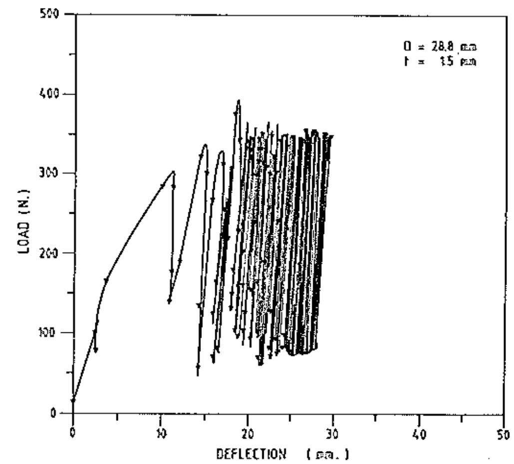

Fig. 11 Cyclic Loading vs. Pile Top Deflection

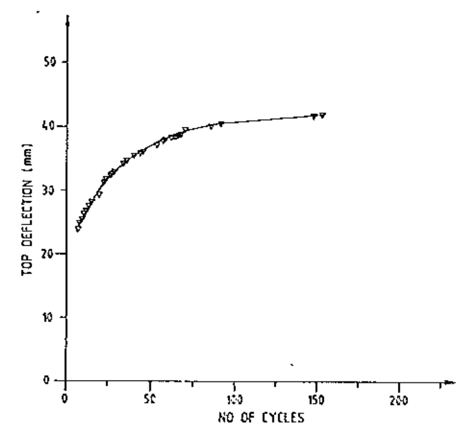

Fig. 12 Variation of max. Deflection with the Number of Cycles

p-y curves (F.D.EXPT). The small deviation is due to the fact that the numerical solution adopts the discrete model for the soil while the soil mass actually is continuous around the pile at all depths. The computed moment utilizing the semi-empirical p-y curves (F.D. THEO) is smaller than the experimental moment because the semi-empirical p-y curves are stiffer than the experimental ones as shown before in Fig. 9.

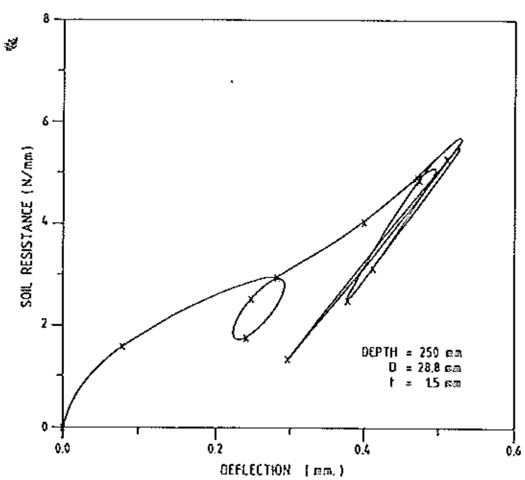

Fig. 13 Moment Variation along the Pile Length for Cyclic Loading

Cyclic loading

The second part of this study is concerned with investigating the behavior of small scale piles subjected to cyclic lateral loading. The maximum applied cyclic load was 85% of the ultimate static capacity. The variation of pile head deflection with cyclic loading is depicted in Fig. 11. It is clear from this figure that large deflection occurs within the initial cycles of loading after which the soil seems to have densified, therefore causing small change in deflection with further increase in number of cycles. This fact can be clarified more by looking into Fig. 12 which shows the variation of deflection with the number of cycles.

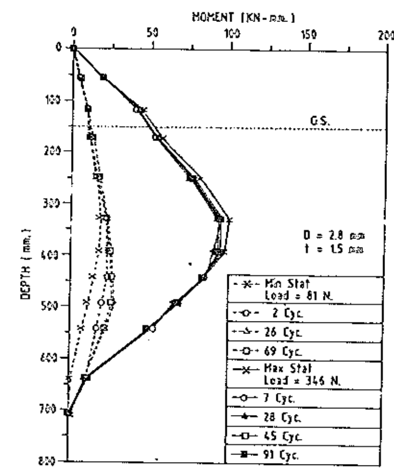

Fig. 14 Experimental p-y Curves at a Depth = 250 mm for Cyclic Loading

Plots of bending moment along pile depth under different load cycles for both minimum and maximum loads are shown in Fig. 13. It is clear from these plots that for the peak cyclic load there is a negligible change in moment as the number of cycles increases. However, for minimum load, the moment increases markedly with number of cycles. This is because the application of the peak loads causes larger deflection than the minimum sustained load which in turn causes molding and softening of sand behind pile surface.

Fig. 14 shows the experimental load-deflection (p-y) curve for one way cyclic loading at a depth of 250 mm. Deflection along the length of the pile was predicted by means of a developed computer program that utilizes the measured strains along the pile length and deflections at the top three points using conjugate beam approach (McCormac, 1984). The deflections and moments curves were utilized to obtain the cyclic p-y curve using simple beam theory discussed earlier. It can be seen that soil resistance tends to stabilize after a few load cycles at that depth level. Unfortunately, there are no theoretical p-y curves available in the literature under such loading condition to compare with the developed experimental curve.

CONCLUSIONS

1. A seven degree polynomial has been developed to best fit the variation of moment along pile length at different load levels.

2. Variation of moment along pile length can best be predicted using a numerical solution utilizing experimental p-y curves. The small variation between the numerical results and experimental ones is because the numerical solution assumes soil to be discrete while it is in reality continuous.

3. The numerical solution with semi-empirical p-y curves does not seem to have good agreement with the experimental results because these curves are stiffer than the experimental ones.

4. For cyclic loading, large deflections at the top of the pile occur within the initial cycles of loading after which deflection seems to stabilize because the soil tends to densify with further load cycles.

5. For peak load, the variation of moment with cyclic is negligible, while it is not the case for minimum sustained load.

6. Under cyclic loading, soil resistance seems to stabilize after the initial cycles of load.

ACKNOWLEDGEMENT

The authors of this paper would like to express their appreciation to King Fahd University of Petroleum and Minerals for providing laboratory space and computer facilities required for this research.

REFERENCES

ABDULJAUWAD, S.N., SHAMEEM, M., AL-SULAIMANI, G.J. & BASUNBUL, I.A. (1990). Study on the Behavior of Model Piles Embedded in Sand. *Paper accepted by Arabian Journal for Science and Engineering, AJSE*, Dhahran, Saudi Arabia.

American Petroleum Institute (1982). *Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platform*. 13th ed. API RP 2A. Washington, D.C.

BROWN, D.A., MORRISON, C. & REESE, L.C. (1988). Lateral Load Behavior of Pile Group in Sand. *J. Geotechnical Engineering Div., ASCE*, GT11, pp. 1261-1276.

KIM, J.B., LAKSHMAN, S.P. & ROBERT, B.J. (1979). Pile Cap Soil Interaction from Full-Scale Lateral Load Tests. *J. Geotechnical Engineering Div., ASCE*, GT5, 643-653.

McCORMAC, J.C. (1984). Structural Analysis. Harper & Row Publishers, New York.

REESE, L.C., COX, W.R. & KOOP, F.D. (1974). Analysis of Laterally Loaded Piles in Sand. Proc. *Offshore Technology Conference, OTC 2080*, Houston, Texas, 473-483.

SHAMEEM, M. (1988). Study of Laterally Loaded Single Pile Model. *M.S. Thesis*, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia.

TING, J.M. (1987). Full Scale Dynamic Lateral Pile Responses. *J. Geotechnical Engineering Div., ASCE*, GT1, 30-45.