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Behaviour of Cyclically Loaded Model Piles in Soft Clay

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SYNOPSIS: Instability studies on offshore piles has been carried out to a very limited extent. Cyclic loading resulting from wave action is a very common phenomenon for such piles. Continuous cycling (both vertical and lateral) presumably leads to substantial degradation in pile-soil response, the ultimate result of which could be disastrous. Over the last decade and a half, some work has been done to study the pile-soil interaction behaviour under repeated cyclic loading. This paper aims to highlight and discuss the salient features and the important observations of extensive model tests on piles subjected to vertical cyclic load. The degradation of pile-soil behaviour with different parameters have been studied, rationally analysed and a set of definite conclusions drawn therefrom.

INTRODUCTION

The majority of offshore structures are supported on pile foundations. Apart from the usual static loads (dead load, live load etc.), these piles are subjected to repeated cyclic loading (both vertical and lateral) resulting from continuous wave action. Presumably, such repeated loading is instrumental in bringing about a progressive loss in pile-soil response manifested by a reduction of the load carrying capacity and pile soil stiffness. A substantial deterioration might finally lead to catastrophic results.

During the past decade and a half, the subject of piles under cyclic loading has been one of the most important issues concerning geotechnical engineers. Some work has been done on the subject but a lot is yet to be done. Most of these works are experimental, based on laboratory and field tests. But, till date, no universally acceptable theory to analyse cyclically loaded piles seems to be in vogue. Current design procedures are thus mostly empirical.

This paper reports the results of extensive experimentations conducted on model piles in the soil Mechanics Laboratory of Jadavpur University, India. Model aluminium and brass piles embedded in soft/medium soft clay beds were subjected to two way cyclic loading. A special pneumatically operated loading device, designed and fabricated indigenously, was used for this purpose. Some rather interesting observations were obtained which were analysed and interpreted categorically and a set of definite conclusions were arrived at. Degradation of both skin friction and end bearing have been evaluated and useful relationships are suggested.

BRIEF REVIEW OF EARLIER WORKS

Some of the earliest known research work in the field of piles under cyclic load were done by Holmquist & Matlock (1976). They conducted model tests on piles under both one way and two way cyclic loading. Substantial loss in skin friction was reported under two-way loading as compared to one-way loading.

Bea et al (1975) had previously suggested the above fact and Broms (1972) also had the same suggestion based on field tests.

Applying the critical state concept, Sangrey (1977) analysed cyclically loaded piles. But the deformations were not accounted for.

Matlock & Foo (1979) considered a pile in a simple and hysteretic soil model and presented an analysis. Soil degradation was considered when a full reversal or yielding in both directions occurred.

Boulon et al (1980) employed the finite element technique to analyse piles in sand. They proposed a hyperbolic relationship between strain and number of cycles.

H.G. Poulos (1979-1982) made pioneering studies for piles under cyclic loading. Poulos (1979) proposed a method of analysis for piles under cyclic loading using the effective stress approach. He supplemented the theoretical analysis with extensive model tests and showed reasonable agreement between the two.

Exhaustive studies on the frictional response of piles under cyclic loading were conducted by Poulos (1981a). He reported considerable loss in skin friction due to load reversal and attributed the cause to particle re-orientation at the pile-soil interface.

H.G. Poulos (1981b) proposed a theoretical analysis based on the effective stress approach and followed it up with number of model tests. He showed that this approach was a more rational one than the effective stress method. It is also much easily applicable and less cumbersome.

To study the effect of cycling on pile capacity and pile-soil stiffness, Poulos (1982) performed number of model tests in the laboratory. Tests were conducted both on single piles and pile groups and on clay and sand. The group effect was found to be much more severe and in sand, the piles tended to show an accumulation of permanent settlements.

Purkayastha & Dey (1989) conducted a large number of model tests to assess the frictional degradation of model piles in soft clay. Two way cyclic loading was applied on the piles at a gradual rate of 1.25 mm/min. Considerable deterioration in skin friction was reported by the authors. An effort was made to predict the cyclic ultimate loads theoretically by using certain experimentally computed degradation factors. Reasonable agreement was observed between the experimental and predicted results.

Further studies on the behaviour of model piles under two-way cyclic load were carried out by Purkayastha & Dey (1990a, 1990b). They used a special pneumatic device to apply cyclic load on piles and the degradation of total and base resistances were observed. The frictional deterioration could easily be seggregated from the results obtained. Certain degradation factors were proposed which were utilised for prediction of cyclic ultimate loads theoretically.

EXPERIMENTAL SET UP AND EQUIPMENTS

A large number of small scale model tests were conducted in the laboratory. The experimental set up and the various components of the apparatus are discussed in brief below.

<u>Loading Device</u>

For conducting some pilot tests under cyclic load recourse was initially taken to the conventional triaxial loading frame with facilities to reverse the direction of load application. By operating appropriate switches, the triaxial base could be raised or lowered thereby applying compressive or tensile loads respectively. Static load tests could also be performed with this device by loading the model pile in compression only.

A more versatile and useful loading apparatus was designed and fabricated by the authors subsequently. This device utilises the pneumatic pressure from an air compressor to operate a double acting piston cylinder. The compressed air is filtered, regulated and lubricated properly before it enters the piston cylinder through a double solenoid operated spool valve. The solenoid reverses the direction of operation at a specified interval of time. This time interval could be monitored by an indigenously manufactured electronic timer system. Details regarding the pneumatic apparatus and its various components will shortly be published elsewhere. The apparatus and the pneumatic connections are shown in Figs. 1 and 2.

<u>Soil Used</u>

For the purpose of the tests, two types of soil were used to prepare homogenous test beds of soft and medium soft clay respectively.

In the first case, for conducting the pilot tests, commercially available kaolin was used as a representative variety of soft clay. Oven dried samples of kaolin were throughly mixed with 60% water and consolidated under a pressure of 0.43 Kg/Cm^2 for 24 hours to prepare the test bed. Routine tests indicated the following properties of the bed :

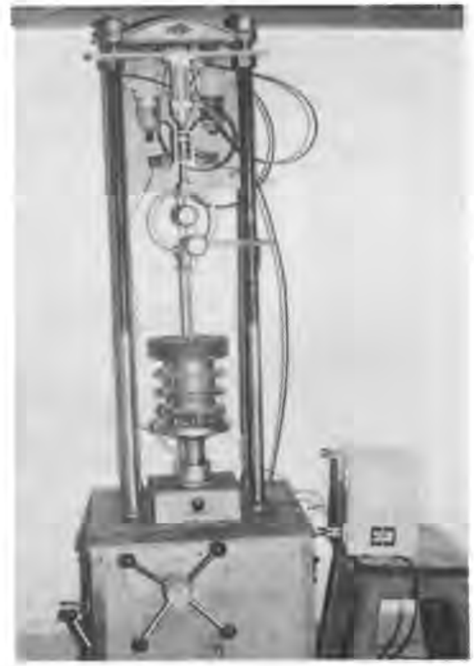

Fig.1 Experimental Set Up for Pneumatic Loading Tests

Fig.2 Details of Connections of Pneumatic Components

Atterberg limits: Liquid limit = 57%
Plastic limit = 33.0%
Plasticity index = 24.0%

Grain size distribution : Clay = 63.2%
Silt = 36.8% , Sand = 0.0%

Undrained cohesion : C_u = 0.179 Kg/Cm^2

In the second type of confirmatory tests, Normal Calcutta Clay was used. This was oven-dried, pulverised and sieved (IS 200 sieve) and mixed with 32% water by weight. The soil mass was then compacted in layers to prepare the test bed and achieve the desired consistency. The engineering properties of the test bed are summarised below:

Atterberg limits: Liquid limit = 48.0%

Plastic limit = 24.0%

Plasticity index=24.0%

Grain size distribution : Clay = 72.0%

Silt = 28.0% , Sand = 0.0%

Undrained cohesion : C_u = 0.184 Kg/Cm^2.

Test Tank

For confining and consolidating the soil, a specially manufactured segmented brass tank was used. The tank consisted of three flanged segments of 100 mm diameter and 50 mm height alongwith a detachable collar and base plate. Facilities for drainage during consolidation was provided through the base. A 6 mm Teflon lining inside the tank reduced the friction between the soil and the tank surface. For conducting tests on friction piles only, a central opening was provided within the base plate so that the pile tip could project out thereby eliminating any base resistance whatsoever.

Model Piles

Model aluminium and brass piles were used to study pile-soil behaviour under cyclic load.

The aluminium piles were made out of solid rods having 15 mm diameter with a tapered base and were used to study the frictional response only under cyclic loading. The pile head was fixed to the loading frame through a proving ring with an adapter. The tip of the pile projected out through the central opening in the base plate so that the applied load was mobilised only by the friction existing between the soil and the pile shaft. The experimental set up with the model pile, test tank etc. is shown in Fig. 3.

The model brass piles in the confirmatory tests were of 12 mm diameter and consisted of an outer sleeve and an inner rod interconnected by a rigid pin. With the pin in position, the pile moved as a whole under the applied load thereby mobilising the load both by skin friction and base resistance. With the pin removed, only the inner rod moved with respect to the outer sleeve thereby mobilising the load only by tip resistance. This facilitated seggregation of the frictional and bearing resistances of the model pile.

Ancilliaries

A number of ancilliary equipments were used to fabricate the test set up and conduct the model tests.

For measurement of load and deflection, standard proving ring and strain dial gauges were used. All pneumatic connections were made by brass connectors of ¼" O.D. to ¼" B.S.P. tapered thread with brass ferrules. Special care was taken to ensure leak proof connections by using teflon thread tapes. The compressed air was channelised by HDPE tubes of ¼" bore with a burst rating of 70 Kg/Cm^2. All pneumatic components were calibrated to withstand a pressure range of 0-150 p.s.i. at 48°C ambient temperature.

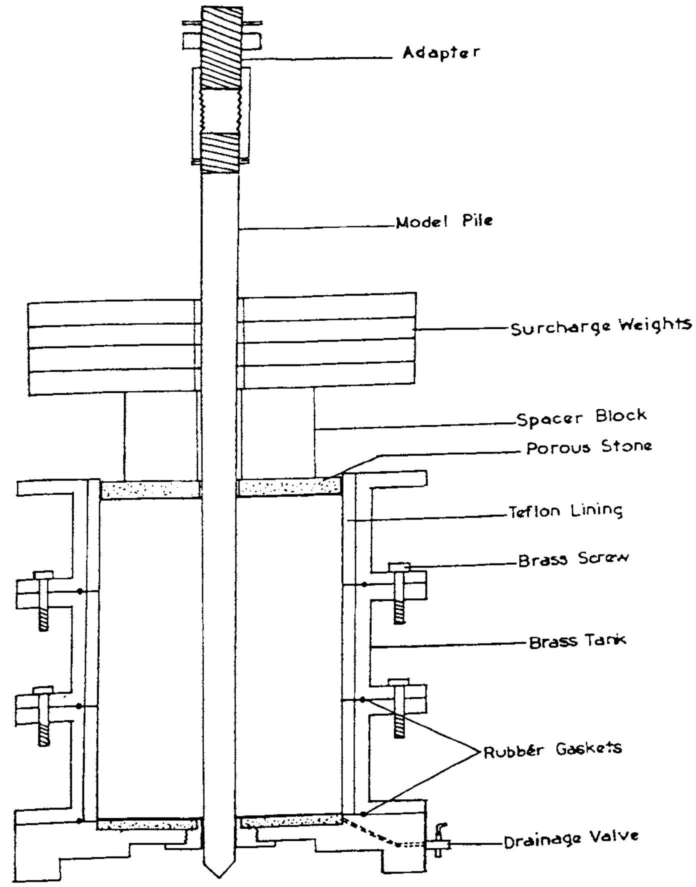

Fig.3 Experimental Set Up for Conventional Loading Tests

MODEL TESTS

Different types of model tests were carried out by subjecting model piles to two-way cyclic loading. The deterioration of pile-soil response was assessed from the analysis of the test results.

Preliminary Tests

A few routine tests were conducted to determine the properties of the test bed. These have been mentioned earlier.

For tests on kaolin, few experiments were conducted to arrive at an optimum curing time of the soil after completion of consolidation. This was done by installation of model pile in the test bed at various time intervals after consolidation followed by ultimate load tests. From the resulting load vs. time curve, the optimum time required for curing could easily be determined.

Similar tests were carried out to arrive at an optimum time for thixotropic strength regain. This was done to ascertain the time required after pile installation and prior to testing. A similar load vs. time curve was obtained from where the required optimum time was determined. This test was done for both kaolin and Normal Calcutta soil.

It may be mentioned here that similar tests were conducted by Poulos (1981a) for his experiments with cyclic loading.

Static Tests

Static tests, both before and after cycling, constituted an important part of the experimental programme. Few initial static tests were conducted on model piles to ascertain the static ultimate loads. For kaolin, this was done only with respect to the frictional component. For Normal Calcutta soil, the tests were carried out for both total and base resistance mobilisation from where the frictional part could easily be seggregated.

After subjecting the model piles to different types of cyclic tests, static tests were performed again in order to assess the cyclic ultimate loads and therefrom the degradation in pile-soil response.

Cyclic Tests

A variety of cyclic tests, which formed the most essential part of the programme, were performed in the laboratory.

Tests with Conventional Apparatus - These were conducted with the help of conventional triaxial loading device. Cycling was achieved by operating appropriate push button switches which reversed the direction of load application as and when desired. The tests (both static and cyclic) were performed at a constant loading rate of 1.25 mm/min. The different types of tests that were carried out were :

1. Load controlled tests
2. Displacement controlled tests

As the names suggest, the above tests were performed by controlling the cyclic load magnitude (P_c) and displacement (ρ_c). Control was achieved by monitoring the proving ring (load) dial and strain (displacement) dial respectively. Cyclic load magnitudes of 10%, 20%, 30%, 40% and 50% of the static ultimate load (P_{us}) were applied. Displacements of 0.5%, 1.0%, 1.5%, 2.0% and 2.5% of the pile diameter (d) were allowed. Both types of tests were performed for 1,2,5,10 and 25 number of cycles. After completion of each cyclic test, a static test was performed to determine the cyclic ultimate loads (P_{uc}).

It may be mentioned here that the above tests were performed on 15 mm diameter aluminium piles with an embedment length of 150 mm into the soft clay bed. The pile tip projected out from the bottom of the tank to eliminate any possible end resistance. Thus, the tests were essentially aimed to assess the frictional response only.

Tests with Pneumatic Apparatus : For these tests, a special pneumatically operated loading device was used. Load was applied by utilising the thrust of a piston operated by compressed air. Details regarding the apparatus have been mentioned earlier. The different types of tests that were performed include :

1. Tests with varying displacement levels
2. Tests with varying loading rates
3. Tests with varying number of cycles

As before, control of displacement was achieved by monitoring the strain gauge for the desired displacement. The displacements allowed were 2.0%, 3.0%, 4.0% and 5.0% of the pile diameter. The rate of load application was controlled by means of an electronic timer system which could be set to obtain the desired frequency of loading. The loading rates used were 10, 20 and 30 cycles/min. All tests were conducted for 10,20,30,40 and 50 number of cycles. A mechanical counter fixed with the timer allowed a visual check on the exact number of cycles applied at any instant of time. Each cyclic operation was followed by a static load test to determine the cyclic ultimate loads.

The above mentioned tests were conducted on brass piles of 12 mm diameter with an embedment of 120 mm in the medium soft clay bed. The model brass pile had a facility to allow the tests to be conducted both for total load (friction and bearing) mobilisation and base resistance mobilisation only. The skin frictional component could easily be seggregated from the test results.

TEST RESULTS AND DISCUSSION

Extensive experimentations on model piles under two way cyclic loading were carried out. These have been discussed in the previous sections. Some of the important and relevant results are presented here. Discussions regarding the test observations follow.

Preliminary Test Results

Results of the preliminary routine tests conducted on the test beds have already been mentioned. The other relevant preliminary test results may be mentioned here :

Optimum curing time, t_{oc} = 2 hours

Optimum time for thixotropic strength regain, t_{ot} = 2 hours.

The relevant load vs. time plots are shown in Figs. 4 and 5.

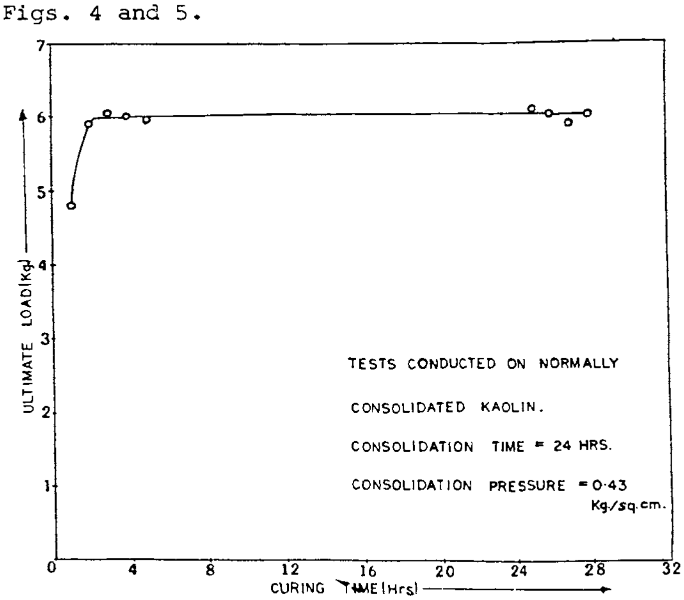

Fig.4 Effect of Curing Time on Ultimate Load Using Conventional Apparatus

Static Test Results

For tests conducted on aluminium piles in soft clay bed (kaolin), the following static test result was obtained :

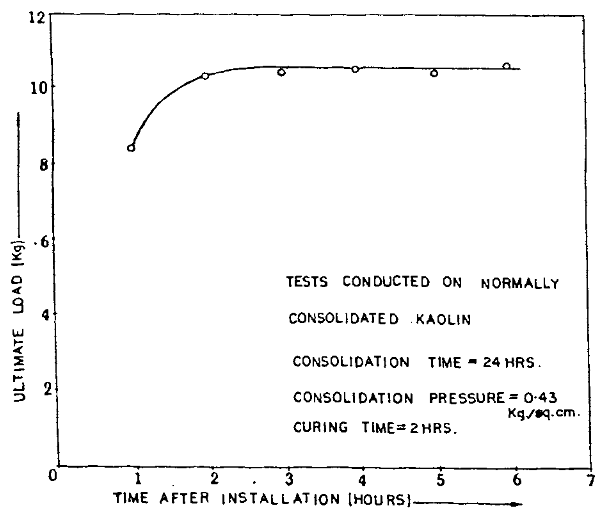

Fig.5 Effect of Time Elapsed After Pile Installation on Ultimate Load Using Conventional Apparatus

Static ultimate load, P_{us} = 10.65 Kg.
(only friction)

The ultimate load was obtained from load-settlement curves corresponding to a pile displacement of 5% of pile diameter. This criterion was fixed for ultimate load determination for all load tests. Other methods as available for determination of ultimate load, were not found suitable.

For tests conducted on brass piles in medium soft clay (Normal Calcutta soil), the following results were observed :

Static ultimate load (total), P_{us} = 8.85 Kg.

Static ultimate load (base resistance), P_{bs} = 3.72 Kg.

Static ultimate load (friction), $P_{fs} = P_{us} - P_{bs}$ = 5.13 Kg.

Cyclic Test Results

A number of cyclic load tests of different types were conducted. These have been discussed earlier. The relevant test results are presented here :

The concept of degradation factors were used. According to Poulos (1979), a degradation factor may be defined as the ratio of a parameter after cycling to that prior to cycling. The same concept has been utilised here to establish the following degradation factors :

Total degradation factor, $D_u = \frac{P_{uc}}{P_{us}}$

Skin friction degradation factor, $D_f = \frac{P_{fc}}{P_{fs}}$

Base resistance degradation factor, $D_b = \frac{P_{bc}}{P_{bs}}$

where, P_{uc} = cyclic ultimate load (total)
P_{us} = static ultimate load (total)
P_{fc}, P_{fs} = corresponding ultimate loads (skin friction)
P_{bc}, P_{bs} = corresponding ultimate loads (base resistance).

These degradation factors have been used as parameters to indicate the deterioration of pile-soil response under cyclic loading.

Tests With Conventional Apparatus

As mentioned earlier, two types of tests were conducted under this series at a rate of 1.25 mm/min. The tests were load controlled and displacement controlled type. The cyclic ultimate loads for each test was determined from the resulting load-settlement curves for a displacement criterion of 5% of pile diameter. These data were processed to obtain the degradation factors according to the methodology mentioned earlier. Full details regarding the test results are available from earlier publication of Purkayastha and Dey (1989).

Tests With Pneumatic Apparatus

Using the pneumatic loading apparatus, a number of tests were performed. Loading rates of 10, 20 and 30 cycles/min. were used and the load was applied through a pneumatically operated plunger. The cyclic ultimate loads were determined from load-settlement curves and were utilised to compute the relevant degradation factors.

ANALYSIS AND INTERPRETATION

The results of the various tests, both static and cyclic and the degradation factors obtained therefrom are categorically analysed and interpreted in a rational manner.

Load-Settlement Pattern

For both static and cyclic tests, definite failure is observed from the load-settlement curves. As mentioned earlier, the load corresponding to a settlement of 5% of pile diameter was considered as the ultimate load. Conventional methods of ultimate load determination were also tried but not found consistent. Typical load settlement curves are shown in Figs. 6-9. It may be observed from these curves that in the case of pneumatic loading, the end bearing component constituted about 42% of the total load implying that the frictional part shared 58% of ultimate load.

Comparisons between the friction ultimate load for conventional and pneumatic loading indicate that the earlier is more than twice the latter. This was expected because in the first case, the pile diameter and embedment length (15 mm and 150 mm) were much more than those in the second case (12 mm and 120 mm).

Influence of Different Parameters on Degradation

Degradation factors were computed for both conventional and pneumatic loading. These may be considered as indicators of the deterioration in pile-soil behaviour. The variation of the degradation factors with different parameters for both types of loading are depicted in Figs. 10-15.

Variation of Degradation Factors With Number of Cycles

From the experimental cyclic ultimate loads for total and base resistances as obtained from pneumatic tests, the frictional resistance could easily be seggregated. These were utilised to compute

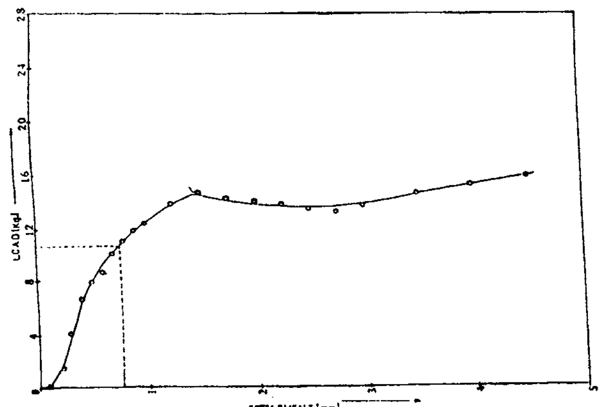

Fig.6 Load-Settlement Pattern for Static Load Test on Kaolin

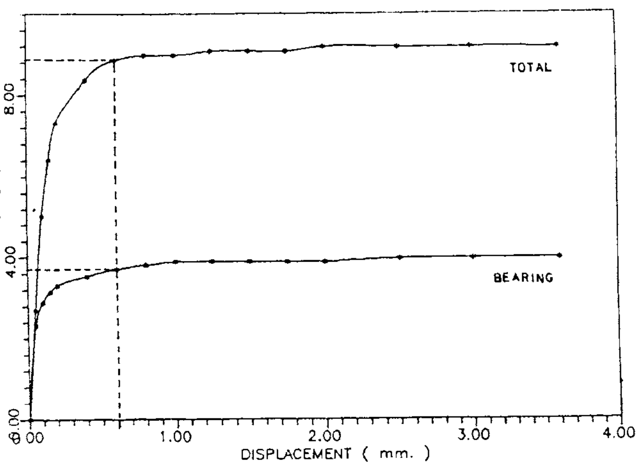

Fig.7 Load-Settlement Pattern for Static Load Test (Total and End Bearing) on Normal Calcutta Soil

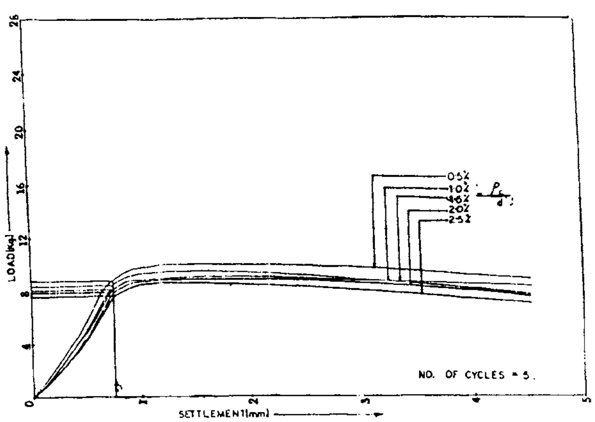

Fig.8 Typical Load-Settlement Curves for Cyclic Load Tests on Kaolin

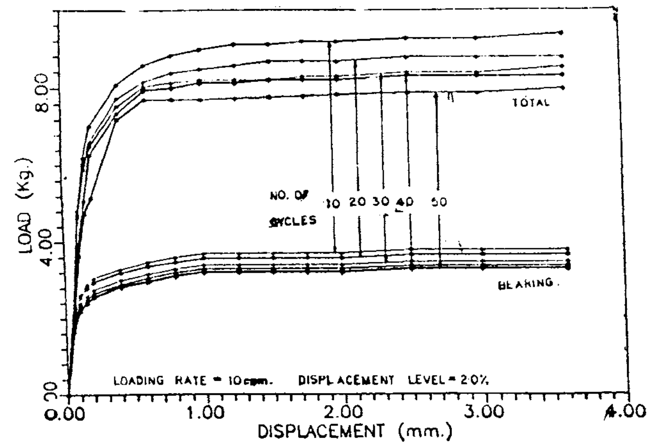

Fig. 9 Typical Load-Settlement Curves for Cyclic Load Tests (Total and End Bearing) on Normal Calcutta Soil

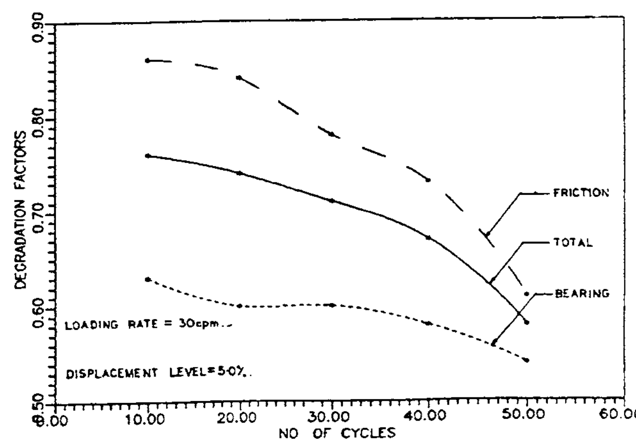

Fig.10 Variation of Degradation Factors With Number of Cycles for Pneumatic Loading Tests

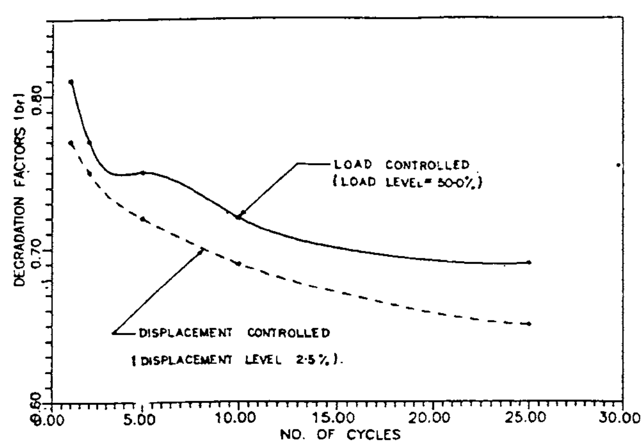

Fig.11 Variation of Degradation Factor With Number of Cycles for Conventional Loading Tests

the skin friction degradation factors. The variation of the degradation factors (total friction and bearing) with number of cycles is shown in Fig. 10 for a loading rate of 30 cpm and a displacement level of 5%. A steady and uniform variation of degradation is noted for all cases. The degradation of base resistance is seen to be more pronounced than the total or frictional degradations, the frictional degradation being the minimum.

For conventional loading, similar curves have been plotted as shown in Fig. 11 for a load level of 50% and a displacement level of 2.5%.

The degradation is seen to be more pronounced for displacement controlled tests than load controlled tests. A uniform variation of degradation is also noted here with increasing number of cycles.

Variation of Degradation Factors With Cyclic Displacement Level

The degradation factors have also been plotted against the cyclic displacement levels. For pneumatic loading, Fig. 12 shows the variation for total, skin friction and base resistance degradation factors for a loading rate of 10 cpm and 30 cycles. As before, the base resistance degradation is seen to be most pronounced in comparison to the total and frictional degradations. The change of degradation is also uniform and is more pronounced at higher displacement levels.

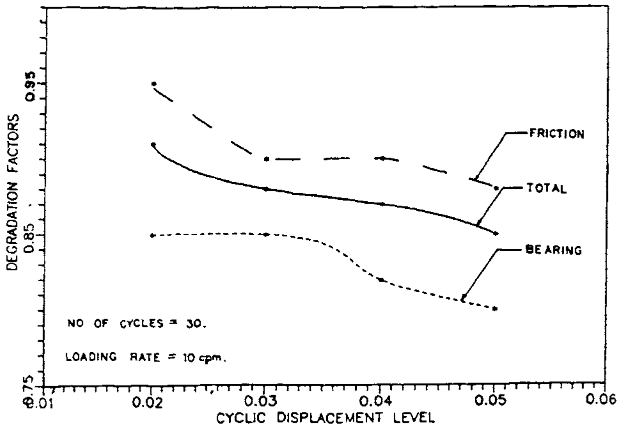

Fig.12 Typical Variation of Degradation Factors With Cyclic Displacement Level for Pneumatic Loading Tests

For the conventional loading case, curve has been plotted for 25 number of cycles. A uniform variation of degradation factor is observed with increasing cyclic displacement levels. This is shown in Fig. 13.

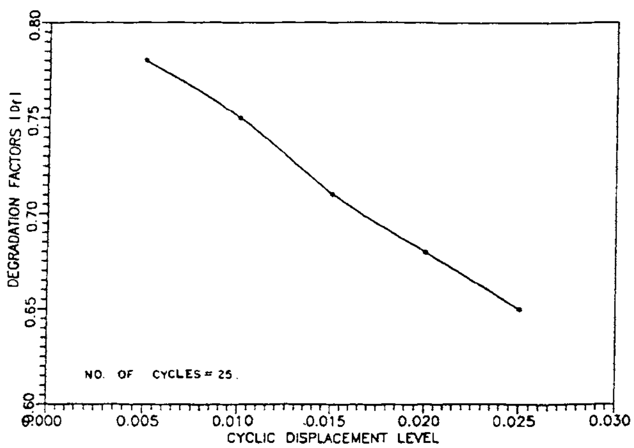

Fig.13 Typical Variation of Degradation Factor With Cyclic Displacement Level for Conventional Loading Tests

Variation of Degradation Factors With Loading Rate/Load Level

For the pneumatic loading tests, the computed degradation factors have been plotted against the loading rate. Loading rates of 10, 20 and 30 cpm were employed. It may be observed that the total and end bearing degradation vary steadily throughout whereas the frictional degradation shows some non-uniform behaviour. After an initial increase, the degradation factor decreases considerably as the loading rate increases. This is depicted in Fig. 14 for a displacement level of 4% and 40 cycles.

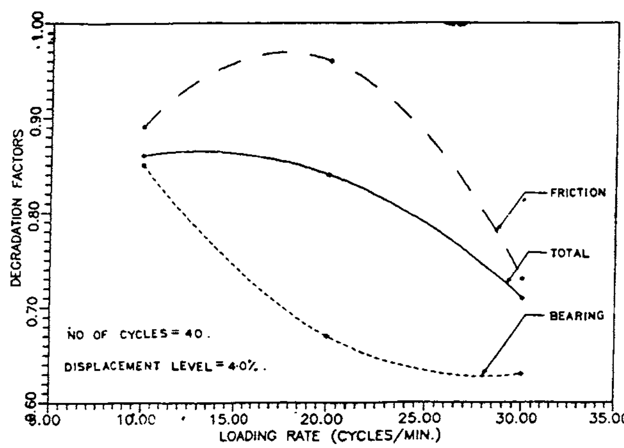

Fig.14 Variation of Degradation Factors With Rate of Loading for Pneumatic Loading Tests

The change of degradation with cyclic load level for conventional loading is shown in Fig. 15 for 10 cycles. The pattern is seen to be non-uniform. The degradation is observed to be least for a load level of 30% and thereafter it decreases steadily with further increase of load level.

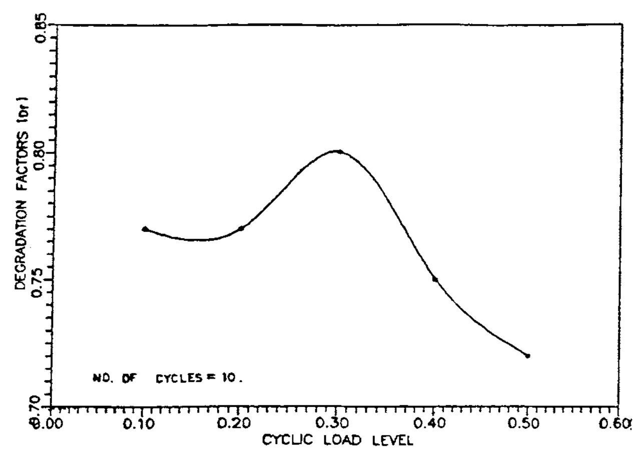

Fig.15 Variation of Degradation Factor With Cyclic Load Level for Conventional Loading Tests

Theoretical Formulation

With the available experimental data, attempt was made for a theoretical formulation to depict the nature of variation of the degradation factors. With computer analysis, it was found that the total variation of total degradation factor with loading rate (for different cycles and displacement levels) may be expressed by the following relationship :

$$D_0 = A + B.L + C.L^2$$

where, D_u = total degradation factor

L = loading rate

A, B, C = constants.

The constants A, B and C vary with the number of cycles and cyclic displacement level. Typical curves to show these variations are given in Figs. 16-18. Full set of results are published elsewhere.

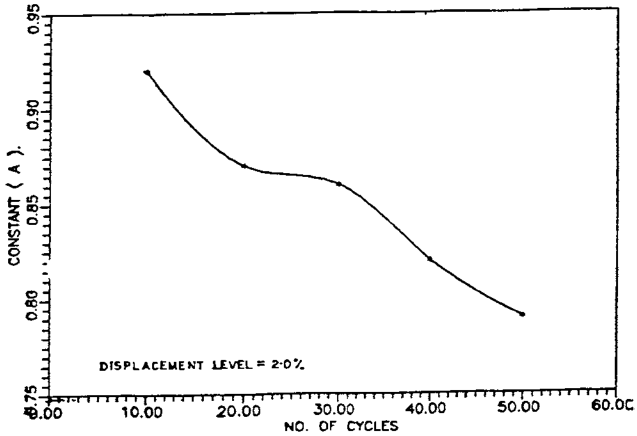

Fig.16 Typical Variation of Constant 'A' With Number of Cycles

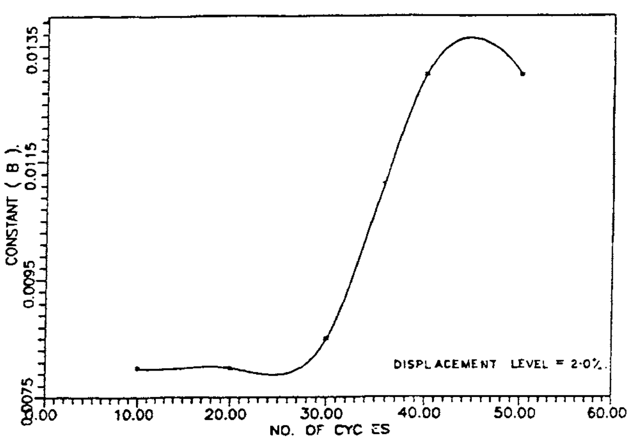

Fig.17 Typical Variation of Constant 'B' With Number of Cycles

Prediction of Cyclic Ultimate Load Using Normal Pile Theory

Using the conventional pile theory, the ultimate load capacity of a pile may be expressed as :

$$Q_u = Q_f + Q_b$$

where : $Q_f = \pi \cdot d \cdot l \cdot \alpha \cdot C_u$

and $Q_b = \frac{\pi \cdot d^2}{4} \cdot C_u \cdot N_c$

where : Q_u = ultimate load capacity of pile

Q_f = load carried by skin friction only

Q_b = load carried by end bearing only

d = pile diameter

l = embedded length of pile

α = adhesion factor

C_u = cohesion of the soil

N_c = bearing capacity factor.

Assuming a suitable 'α' value depending on the consistency of the clay bed, the theoretical pile capacities worked out as :

For 15 mm diameter pile : $Q_u = Q_f = 11.39$ Kg.

For 12 mm diameter pile : $Q_u = 8.35$ Kg.

$Q_f = 5.02$ Kg.

$Q_b = 3.33$ Kg.

The theoretical computations show that the frictional and end bearing components of the total load are 60% and 40% respectively as compared to 58% and 42% obtained from experimental data.

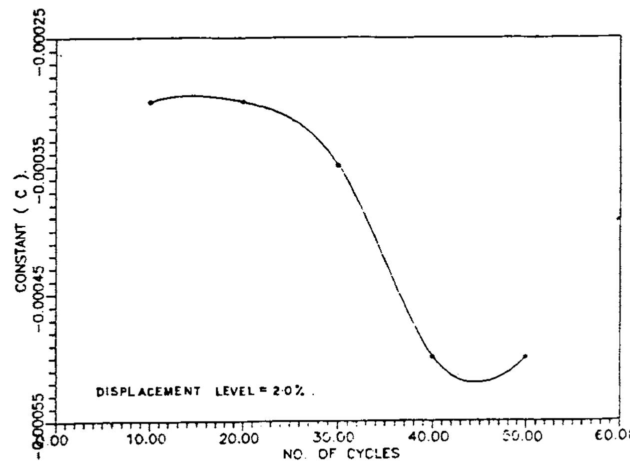

Fig. 18 Typical Variation of Constant 'C' With Number of Cycles

Using the experimentally obtained degradation factors and the theoretical loads, an attempt was made to predict the cyclic ultimate loads theoretically. Typical comparison curves between the predicted and experimental values are shown in Figs. 19-20.

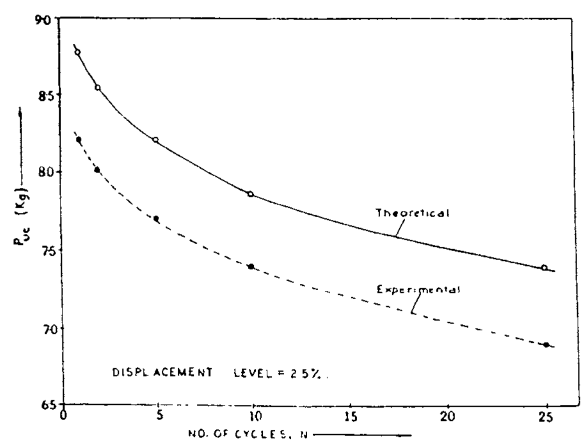

Fig.19 Comparison Between Theoretical and Experimental Cyclic Ultimate Loads for Conventional Loading Tests

For conventional loading, an overall variation of 7% was noted with the theoretical values being on

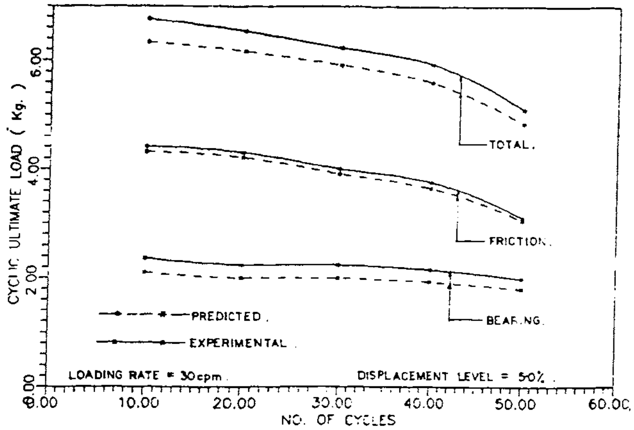

Fig.20 Comparison Between Predicted and Experimental Cyclic Ultimate Loads for Pneumatic Loading Tests

the higher side. On the contrary, for rapid loading, an average variation of 6% was noted with the experimental values being on the higher side.

CONCLUSION

In order to rationalise pile-soil behaviour under two-way, vertical cyclic load, extensive experimentations were conducted. The experimental data obtained were analysed and interpreted in a rational manner to arrive at some definite conclusions. For the purpose of the tests, aluminium and brass model piles of 15 mm and 12 mm diameter were used. These were embedded in soft and medium soft clay beds and subjected to cyclic loading. Conventional and pneumatic loading were employed using a triaxial device and a pneumatic apparatus respectively. Considerable deterioration was observed in pile-soil response. In the pneumatic tests facilities for seggregating friction and end bearing were provided.

For conventional loading, the variation of degradation is seen to be uniform with number of cycles and cyclic displacement level. But with cyclic load level, somewhat non-uniform variation is observed with the degradation being minimum at a load level of 30%. For pneumatic loading also steady degradation is observed with number of cycles and displacement level. With rate of loading however, the variation shows some non-uniformity. The total degradation factor varies with the loading rate according to a second order equation as established after a computer analysis. The experimental degradation factors are utilised to try and predict the cyclic ultimate loads theoretically. For conventional loading, an overall variation of 7% and for pneumatic loading, an average variation of 6% are observed between the experimental and predicted cyclic ultimate loads.

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REFERENCES

Bea, R.G., Audibert, J.M.E. and Dover, A.R. (1980), "Dynamic Response of Laterally and Axially Loaded Piles", Paper OTC 3749, Proc. 12th Offshore Technology Conference, Houston, Texas, pp. 129-139.

Boulon, M., Desrues, J., Foray, P. and Forgue, M. (1980), "Numerical Model for Foundation Under Cyclic Loading, Application to Piles", Int. Symposium, Soils Under Cyclic and Transient Loading, Swansea, Wales, A.A. Balkema, Rotterdam, pp. 680-694.

Broms, B.B. (1972), "Bearing Capacity of Cyclically Loaded Piles", Report No. 44, Swedish Geotechnical Institute, Stockholm, Sweden, pp. 1-16.

Holmquist, D.V. and Matlock, H. (1976), "Resistance-Displacement Relationships for Axially Loaded Piles in Soft Clay", Paper OTC 2474, Proc. 8th Offshore Technology Conference, Houston, Texas, pp. 554-569.

Matlock, H. and Foo, S.C. (1979), "Axial Analysis of Pile Using a Hysteretic and Degrading Soil Model", Proc. Conference on Numerical Methods in Offshore Piling, Institution of Civil Engineers, London, pp. 99-106.

Poulos, H.G. (1979), "Development of an Analysis for Cyclic Axial Loading on Piles", Proc. 3rd International Conference on Numerical Methods in Geomechanics, Aachen, Germany, Vol. 4, A.A. Balkema, Rotterdam, pp. 1513-1530.

Poulos, H.G. (1981a), "Some Aspects of Skin Friction of Piles in Clay Under Cyclic Loading", Geotechnical Engineering, Vol. 12, No. 1, pp. 1-17.

Poulos, H.G. (1981b), "Cyclic Axial Response of Single Pile", Journal of Geotechnical Engg. Divn., ASCE, Vol. 107, No. GT7, pp. 41-58.

Poulos, H.G. (1982), "Influence of Cyclic Loading on Axial Pile Response", Proc. 2nd Conference on Numerical Methods in Offshore Piling, Austin, Texas, pp. 419-440.

Purkayastha, R.D. and Dey, S. (1989), "Degradation of Soft Clay Under Axial Cyclic Load on Piles", Proc. Indian Geotechnical Conference, Vishakhapatnam, Vol. 1, pp. 81-85.

Purkayastha, R.D. and Dey, S. (1990a), "Piles Under Cyclic Load Using a Pneumatically Operated Device", Paper accepted for publication, Indian Geotechnical Conference, Bombay.

Purkayastha, R.D. and Dey, S. (1990b), "Response of Piles Under Axial Oscillatory Load", Paper accepted for publication, First International Seminar on Soil Mechanics and Foundation Engg. of Iran, Tehran.

Sangrey, D.A. (1977), "Response of Offshore Piles to Cyclic Loading", Paper OTC 2944, Proc. 9th Official Technical Conference, Houston, Texas, pp. 507-512.