Lateral Resistance of a Field Model of Pile Group in Sand and its Comparison with a Laboratory Model

by

Alam Singh*

R.K. Verma**

Introduction

PILE foundations are provided under various heavy structures where the loads are to be transmitted to greater depths through weaker strata and, in many cases, where the lateral loads are to be resisted. The behaviour of pile foundation with respect to soil and loading conditions is of utmost importance to the designer as well as to the field engineer. Theoretical approach to the solution of pile behaviour has been reported by a number of investigators, such as Culmann (1866), Westergaard (1917), Hrennikoff (1949), Vesic (1956, 61), Reese and Matlock (1956, 60), Davisson (1960), and Aschenbrenner (1967). Methods of analysis based on laboratory tests have been reported by Davisson and Gill (1963), Prakash (1962), Murthy (1964) and Singh (1969). Results of field tests and consequent analyses are available from the works of investigators such as Feagin (1937, 53), Gleser (1953), O'Halloran (1953), Wagner (1953), and Mason (1956).

The field tests should yield the most rational approach for understanding the soil pile behaviour. However, the variable and uncontrolled soil conditions restrict the use of a field test of a particular site to be fruitfully utilised for another site where the conditions differ. Moreover, the soil variation at the same site itself make it difficult to verify or check the validity of the theoretical formulations used in the pile analysis. Large scale model field tests under controlled soil conditions should, therefore, be considered very helpful for understanding the soil-pile behaviour or developing a theoretical analysis.

Scope

The scope of the present investigation was to conduct large scale model test on a single pile and a four-pile group under lateral loading in a soil deposit of controlled density. Mild steel pipes, 6 cm in outside diameter and 5 m in length, were used as model piles. The group consisted of four piles arranged in a square pattern at centre to centre spacing of 3 times the pile diameter and rigidly welded to a pile cap. Tests were carried out in medium fine, air-dry sand at a density index of 64 percent. The

* Professor of Civil Engineering and Head of Civil Engineering Department, University of Jodhpur, Jodhpur.

** Lecturer in Civil Engineering, Faculty of Engineering, University of Jodhpur, Jodhpur.

This paper in the present form was received on 1 July 1972. It is open for discussion up to September 1973.

piles were fully embedded and lateral loads were applied at the ground line. The behaviour of the group has been compared with that of the single pile.

Instrumentation and Materials Used

The instrumentation included the fabrication of pile and pile caps, construction of a test well and development of load applying and measuring devices.

PILE

Mild steel pipes, 6 cm outside diameter and 5.5 cm internal diameter, were selected as the piles for the model tests. The length of the pile was decided on the basis the minimum non-dimensional length coefficient 5 (Davisson, 1960) so as to consider it as an infinitely long pile. Five metre long piles were adopted for which the length coefficient worked out to be 12·7 on an assumed value of modulus of subgrade reaction equal to 0·5 kg/cm^3. The relative stiffness (EI) of the piles was experimentally measured as $46{\cdot}65 \times 10^6$ kg-cm^2 by supporting the pile horizontally near the ends on rollers and applying central loads.

PILE CAPS

Mild steel plate, 64·5 cm by 64·5 cm by 2·54 cm thick, was used as the cap for the four-pile group. Four holes of 6 cm diameter at centre to centre spacings of 3 times the pile diameter were drilled in a square pattern in the middle of the plate. The ends of the piles were inserted in the holes from under-side of the plate and projected by 2 cm on the upper side. The piles in that position were welded to the cap. A hole, 2·5 cm diameter was drilled on the centre line of cap at an edge distance of 7 cm for engaging the hook for lateral loading.

The single pile was welded to a cap, 25 cm by 15 cm made of angle irons as detailed in Figure 1.

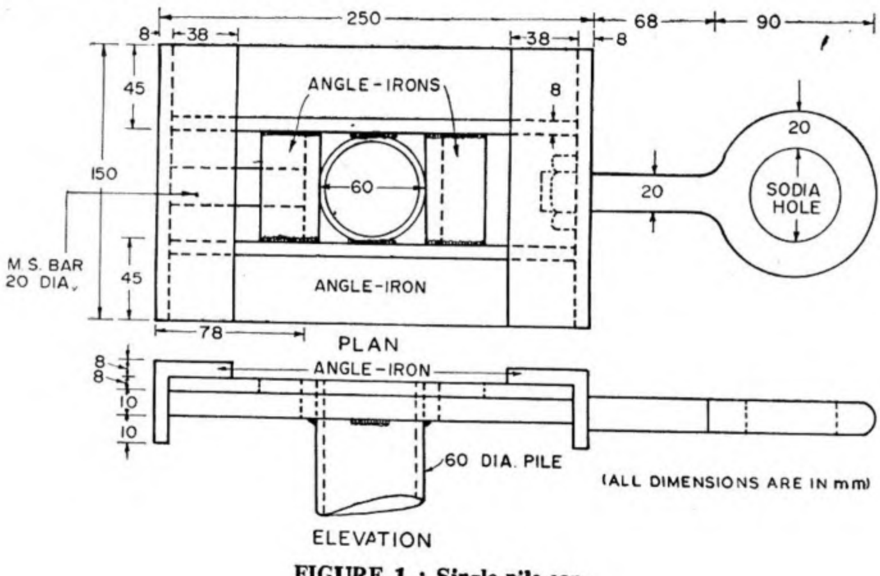

FIGURE 1 : Single pile cap.

TEST WELL

To apply the horizontal load at the pile cap and to measure its lateral deflection, it was thought convenient that the piles should either be driven or placed below the ground surface. Driving the pile in natural strata does not necessarily provide the uniform density throughout the pile length. This could be achieved if the piles were placed in a test well to be artificially filled in layers and compacted to any desired density. A test well deep enough to accommodate the full length of the pile and wide enough to avoid the wall effect was necessary. A stone masonry well with 30 cm thick walls was constructed 3 m in diameter and 5.5 m in depth. It projected about 40 cm above the natural ground level. U-type mild steel brackets were embedded in the steining of the well at 80 cm intervals to serve as a ladder.

LOAD APPLYING AND MEASURING DEVICE

A sliding frame-work of mild steel channels and rods with a vertical R.S. joist embedded into the ground was fabricated to apply the lateral load. As shown in Figure 2, the frame consisted of four channels A, B, C and D, each channel being 12·5 cm by 6·5 cm and 50 cm long. Channels A and D are rigidly connected to each other by means of two mild steel bars, X-1 and X-2, each 28 mm in diameter and 113 cm long with threads on either end for a length of 3·5 cm. The rods X-1 and X-2 are freely movable through 32 mm diameter holes in the other two channels B, and C near their ends. Channels B and C are connected to each other by means of four, 22 mm diameter mild steel bars, two on each side. Each bar is 48 cm long with threads on either end for a length of 4 cm. A calibrated ring, 10 tonnes in capacity accurate to 6·9 kg per division (0·00254 mm) of the dial-gauge, is fitted with bolts between the channels C and D. A 28 mm diameter threaded rod 62 cm long, with hook on one

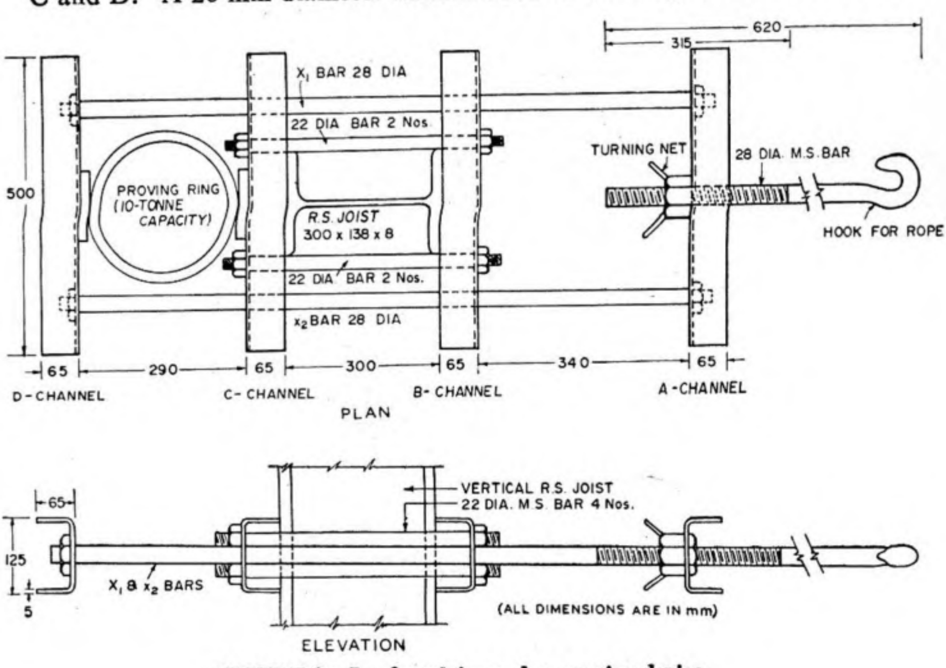

FIGURE 2 : Load applying and measuring device.

end and turning nut on the other end is provided in the centre hole of channel A. The whole assembly is fitted to a vertical R.S. joist, 300 mm by 138 mm, by means of fixing the channels B and C on its faces with the help of four above described bars of 22 mm in diameter and 48 cm long. The joist is embedded to a depth of 3 m into the ground through concrete pads, 1 m by 0·6 m by 0·6 m thick, one pad being at the bottom of the joist and the other just below the ground surface. The joist is 4·6 m away from the centre of the well and its faces are perpendicular to the well diameter along which the lateral load is applied. The lateral load set-up is shown in Figure 3.

DEFLECTION MEASURING DEVICE

A vernier calliper accurate to 0·02 mm was used to measure the lateral deflection and also the tilt with reference to fixed datums as described subsequently.

SOIL MATERIAL

It is a medium fine sand falling in the (SW-SP) group of the Unified Soil Classification System (1962). The grain size analysis curve of the soil is given in Figure 4. The specific gravity of sand is 2·67, effective size 0·092 mm, uniformity coefficient 6·6 and coefficient of curvature 0·44. The test density index was 64 percent.

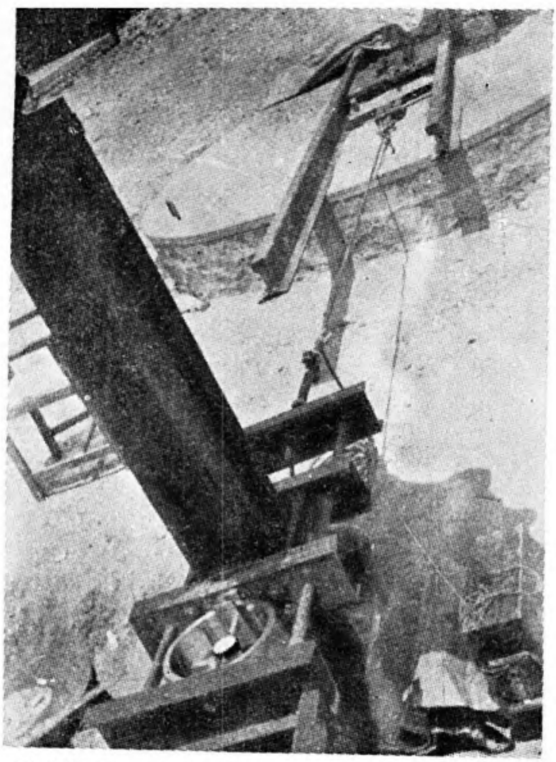

FIGURE 3 : Photo showing set-up for lateral loading.

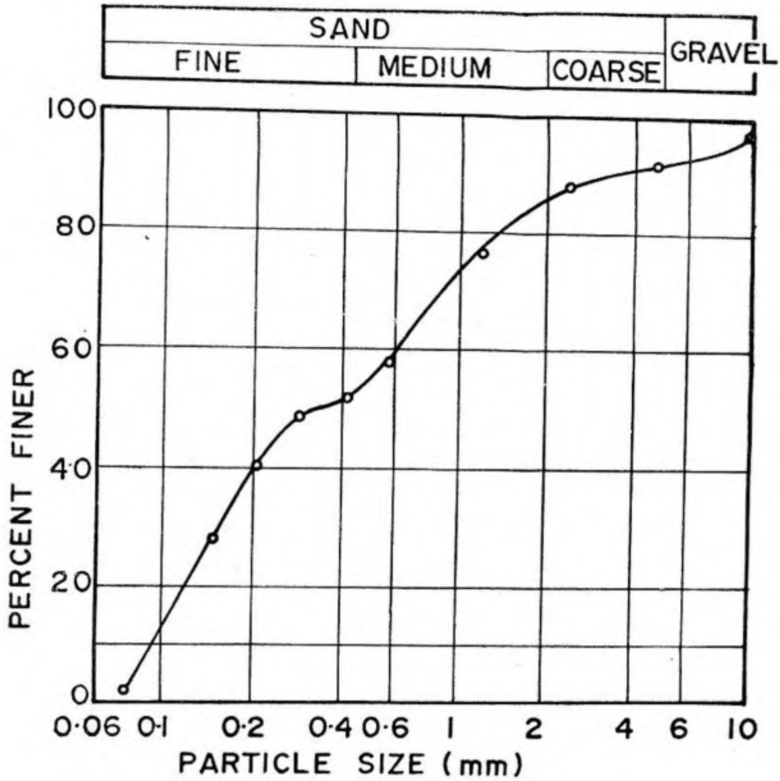

FIGURE 4 : Grain size distribution curve.

Test Procedure

ERECTION OF PILES

The four-pile group was directly supported on the lower flanges of the two horizontal and parallel rails which were placed on the top of the well steining. The rails were equidistant from the diametrical vertical plane passing through the centre line of the R.S. joist flange and perpendicular to it. The rails were kept 72 cm apart from each other. Four wooden wedges of about 3 cm length, one at each corner of the cap, were provided between the lower flanges of rails and the cap of four-pile group. These wedges helped to lift the cap by 6 cm above the top of well steining which was considered as the ground level for piles. The single pile was also supported on the rails with the help of two parallel angle-irons which were placed on the lower flanges of the rails. The single pile was placed in front of the group and their centres were lying on the diameter along which the lateral load was applied. The four-pile group cap was kept a little higher than the single pile cap so as to avoid any obstruction due to single pile while applying lateral load to the group. To maintain a constant spacing between the piles in the group throughout their length, a wooden template 38 cm by 38 cm and 2·5 cm thick corresponding to the top cap was temporarily fitted to the lower ends of the piles. The piles were adjusted true to plume. The open ends of the piles were closed with 12 cm long wooden blocks. Figure 5 shows the erected piles in the well.

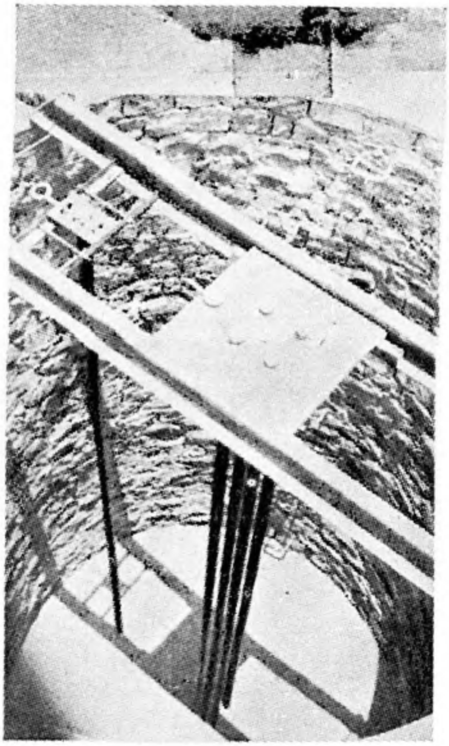

FIGURE 5 : Photo showing piles erected in the test well.

FILLING THE TEST WELL

Jute bags full of about 35 kg of sand were lowered into the well with the help of rope. The soil so lowered was spread in about 25 cm thick uniform layer. During the placement of the first layer, the vertical position of piles was again checked from all the four sides with the help of plumb-bob. The wooden template provided at the lower ends of the group was also carefully removed at that time. The layer thereafter was compacted by two similar form vibrators operating simultaneously on either sides of the pile or pile group. Forty-five minutes were allowed for operation of vibrators for each position and no place was left without being compacted by the vibrators. In order to compact sand inside the group, one M.S. iron plate, 5 cm wide, was placed through the pile group, extending beyond the piles. The two ends of the plate were simultaneously vibrated under the vibrators. After compaction in one direction, the plate was placed in perpendicular direction through the pile group and was vibrated. The test well was filled in such 22 layers and each layer was given similar compaction. To compact the soil beneath the rails and the pile caps in the last two layers, iron plates, placed perpendicular to the direction of rails and extending beyond them, were simultaneously vibrated from the two ends. The top soil layer was in the level of the top of well steining and it constituted the ground surface for the pile. After filling the test well, the horizontal levels of the pile caps were checked and found in order.

FIXING THE LOAD APPLYING AND MEASURING DEVICE

The load applying device was fixed to the R.S. joist in level with the pile cap. Two channels B and C of load applying device were fixed to the flanges by means of four 22 mm diameter bars. Channels A and D were connected to each other by means of two 28 mm diameter mild steel bars and were free to move. The bars were passing through 32 mm diameter holes in the other two channels. A proving ring of ten tonne capacity was fixed between channels C and D with the help of two screws, one in each channel. A 28 mm diameter M.S. hooked bar, with hook towards the pile, was provided in the centre hole of channel A and a turning nut was screwed on its other end. With the movement of turning nut, the bar could be screwed on in backward and forward directions. One end of a 13 mm diameter steel rope was tied with the hook of the load applying device and another end to the hook of the pile cap. The whole arrangement kept the centres of proving ring, hook of load applying device and the pile cap in one line of the application of the load. Figure 6 shows the position of the piles in plan with respect to the well steining.

MEASUREMENTS OF LOAD AND DEFLECTIONS

The lateral load on the pile could be applied by rotating the turning nut in clockwise direction. This stretched the rope and brought the proving ring in compression. The load could be released if the turning nut was rotated in anti-clockwise direction.

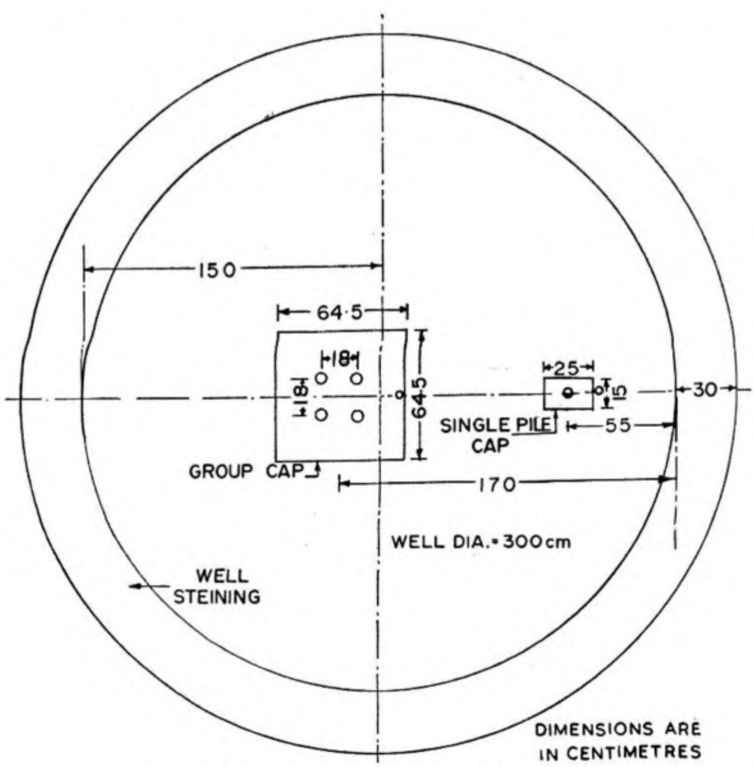

FIGURE 6 : Positions of piles in test well.

Before starting the loading of the single pile, the supporting angle irons were removed from underneath the cap. A seating loading of about 7 kg (equivalent to one division of the proving ring dial-gauge) was applied and released. Lateral load on single pile was then applied in increments of 5 divisions of the proving ring dial-gauge up to 40 divisions, and thereafter in increments of 10 divisions up to a maximum of 120 divisions. Each load increment was kept constant till the horizontal deflection of the pile cap almost ceased. The horizontal deflection of the cap was measured with the help of a vernier calliper (Least count = 0·02 mm) which was fixed on the rear edge of the cap. Every-time its position with respect to a fixed bar on the rails was recorded. The load after the final reading of 120 divisions was released and the residual deflection of the pile was recorded.

To test the group, the supporting wedges of the cap were first removed. The group was loaded to a seating load equivalent to three divisions of the proving ring dial-gauge which was then released and the dial-gauge was adjusted to its zero reading. The lateral load was first applied in increments of 10 divisions up to 40 divisions and thereafter in increments of 20 divisions up to a maximum of 320 divisions of the proving ring dial-gauge. As before, each increment was kept constant for sufficient time so as to gain the full lateral deflection of the pile cap under that increment. The load after the final reading was released. The horizontal deflection was recorded by means of the vernier calliper with respect to the fixed plates on the rails. The rotation was also recorded by measuring the levels of front and rear edges of the cap with respect to the fixed plates which served as the datum levels.

Observations

The observations are recorded in Tables I and II.

Test Result and Discussion

Single pile and four pile-group were subjected to incremental lateral load applied at ground surface. The horizontal deflection Y_g and

TABLE I

Observations on Single Pile.

Lateral Load		Horizontal displacement (mm)	Lateral Load		Horizontal displacement (mm)
Divisions of proving ring dial-gauge	kg		Divisions of proving ring dial-gauge	kg	
0	0·0	0·0	50	345.0	15·13
5	34·5	0·45	60	414·0	19·99
10	69·0	0·85	70	483·0	26·87
15	103·5	1·95	80	552·0	34·35
20	138·0	3·05	90	621·0	42·39
25	172·5	4·69	100	690·0	51·39
30	207·0	6·49	110	759.0	69·00
35	241·5	8·17	120	828·0	93·00
40	276·0	10·55	0	0	63·00

TABLE II

Observations on Pile-group.

Lateral Load		Horizontal displacement (mm)	Rotation Readings		Lateral Load		Horizontal displacement (mm)	Rotation Readings	
Divisions of proving ring dial-gauge	kg		Back (mm)	Front (mm)	Divisions of proving ring dial-gauge	kg		Back (mm)	Front (mm)
0	0	0	0	0	120	828·0	8·24	1·82	— 2·2
10	69·0	0·20	0	0	140	966·0	11·68	3·00	— 3·34
20	138·0	0·34	0·02	0	160	1104·0	16·14	4·30	— 4·78
30	207·0	0·56	0·12	0	200	1380·0	27·04	8·66	— 7·80
40	276·0	0·96	0·20	—0·10	240	1656·0	40·04	13·42	—11·90
60	414·0	2·10	0·52	—0·20	280	1932·0	58·34	18·82	—15·50
80	552·0	3·66	0·90	—0·60	320	2208·0	75·00	24·32	—17·80
100	690·0	5·34	1·20	—1·30	0	0	50·74	16·82	—11·30

rotation of the cap at ground level were measured. The measured horizontal deflection versus lateral load on single pile or average pile load on group are plotted in Figures 7 and 8. Figure 7 gives the horizontal deflection in millimetre as measured while in Figure 8 deflection has been expressed as percentage of pile diameter. The total lateral load on the group divided by the number of piles in the group has been taken as the average load per pile and has been plotted as such in Figures 7 and 8. The rotation of group cap with respect to total lateral loads is shown in Figure 9. To compare the relative behaviour of group with respect to single pile, the relative horizontal deflection at ground line (Y_{gr}) and relative horizontal resistance (Q_{gr}) are computed. The relative horizontal deflection may be defined as the ratio (expressed as percentage) of the horizontal deflection of a pile group to the horizontal deflection of the single pile when the

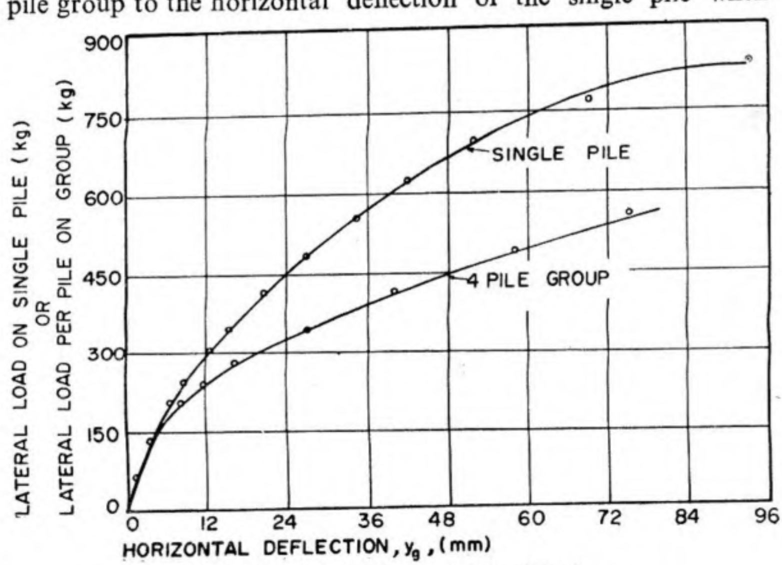

FIGURE 7 : Y_g versus lateral load.

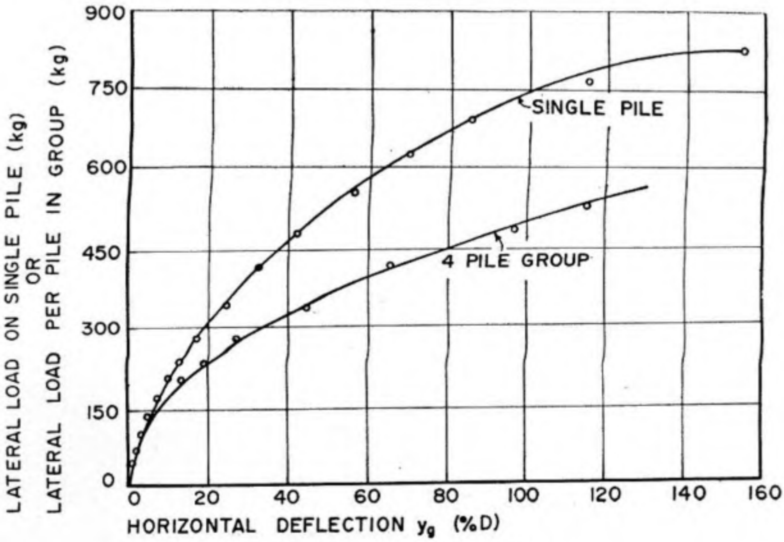

FIGURE 8 : Y_g versus lateral load.

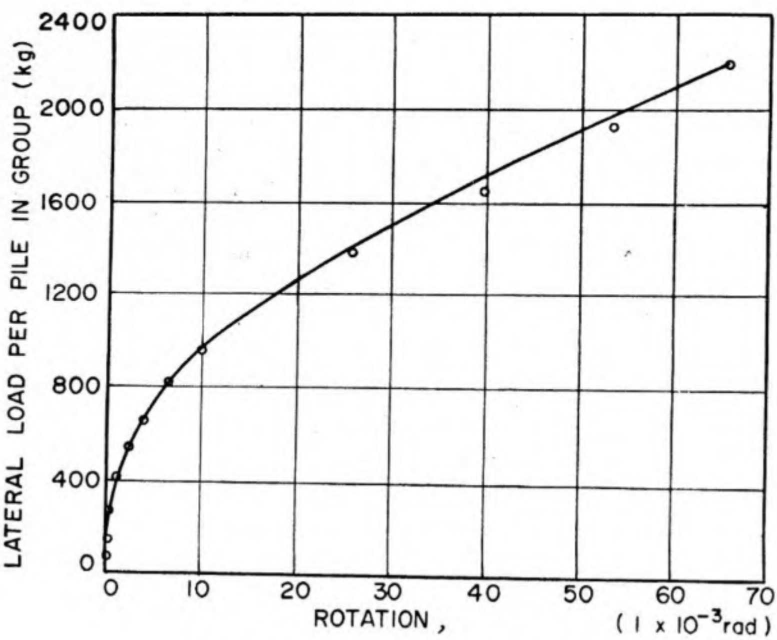

FIGURE 9 : Rotation versus lateral load.

average horizontal load on a pile of the group is equal to the load on the single pile (Singh 1969). Similarly Q_{gr} is the ratio of the average horizontal load on a pile of the group to the horizontal load on the single pile for equal horizontal deflections at the ground line (Singh 1969). Q_{gr} is expressed as a percentage.

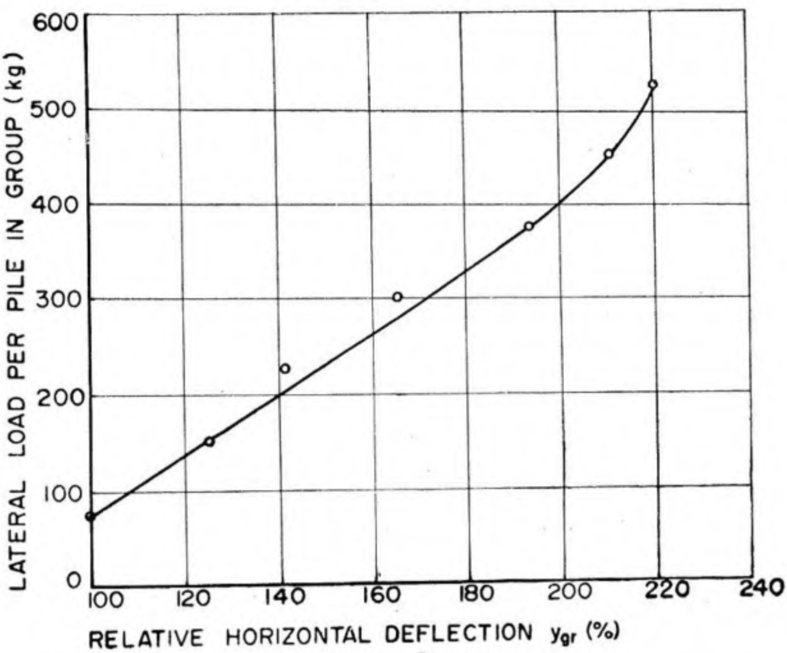

FIGURE 10 : Y_{gr} versus lateral load.

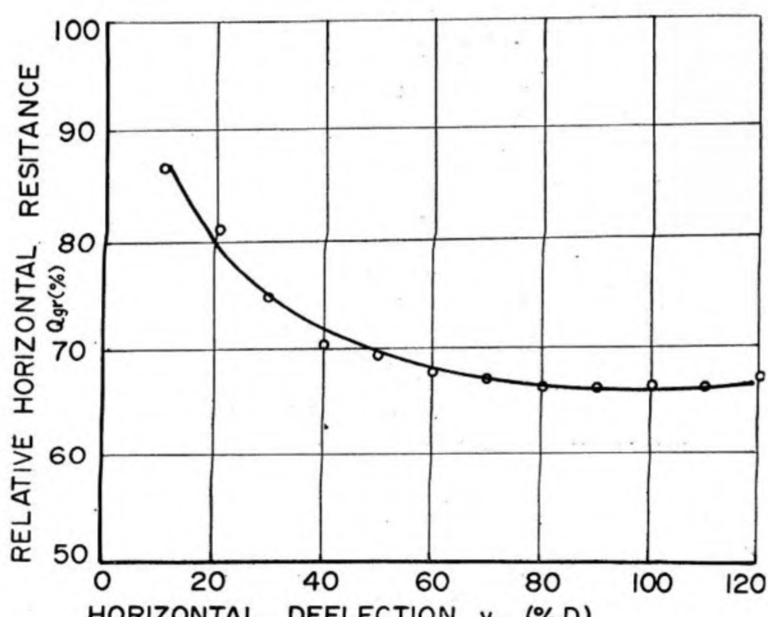

FIGURE 11 : Y_g versus Q_{gr}.

The study of the graphs leads to the following inferences :

(*i*) The horizontal deflection of both the single pile and the group increases non-linearly with the increasing lateral load. The deflection curves go on becoming flatter and flatter on large lateral loads which indicate that the lateral resistance of soil-pile system decreases at larger deflection (Figures 7 and 8).

(*ii*) The rotation of the cap of the pile group also increases with increasing lateral load as indicated in Figure 9.

(*iii*) The relative horizontal deflection, Y_{gr} (Figure 10) is a function of the load. For the four pile-group under study it varies from about 100 percent at lower loads to about 220 percent at higher loads.

(*iv*) The relative horizontal resistance, Q_{gr} sharply decreases as the deflection increases at lower values (say up to 40 percent D). Q_{gr} becomes almost constant and independent of Y_g after Y_g $=50$ percent D (Figure 11).

To know the validity of laboratory tests in comparison to the field tests, results of laboratory tests on small model piles conducted by Singh (1969) are compared with the present findings. As a part of investigations of pile groups under lateral and vertical loads, Singh (1969) tested a number of model pile groups in the laboratory. Aluminium alloy tubes, 1·27 cm square in section and 63·5 cm in length, were used as model piles. Clean, medium-fine sand wholly passing through a 1·18 mm sieve and 94 percent retaining on the 212-micron sieve and having a uniformity coefficient of 2·4, was deposited by vibration in a test tank to form the soil medium for pre-erected pile groups. The pile groups consisted of 4, 9 and 16 piles at varying pile spacings. Horizontal loads were applied at the ground line. Typical load-deflection curves for a 4-pile group at pile spacing of three times the pile width in dense sand (density index=80 percent) and for a single reference pile are shown in Figure 12.

The ratios of lateral load per pile on group to the lateral load on single pile corresponding to 10 percent D and 20 percent D versus relative horizontal deflection, both for the field and laboratory tests have been plotted in Figures 13 and 14 respectively. Similarly the relative horizontal resistance versus horizontal deflection (percent D) for both the laboratory and field tests are plotted in Figure 15. The close resemblance of the behaviour of the laboratory model test and the large scale field model test on long piles indicated by non-dimensional plots of Figures 13, 14 and 15 confirms the validity and the utility of laboratory model tests in predicting the behaviour of actual piles in the field.

Conclusion

The present field investigations on the lateral resistance of a large scale model pile-group and a single pile lead to the conclusion that the pile group with pile spacing of three times the pile diameter offers less resistance to deflection-compared to a single pile under similar conditions of loading. With increase of deflection the resistance of both the group

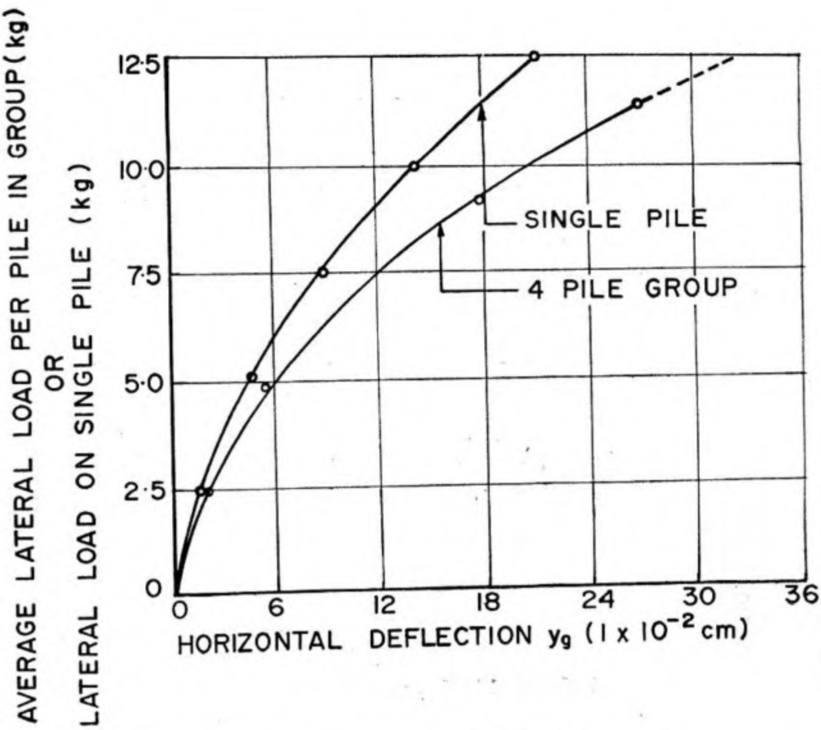

FIGURE 12 : Y_g versus lateral load. Singh, 1969.

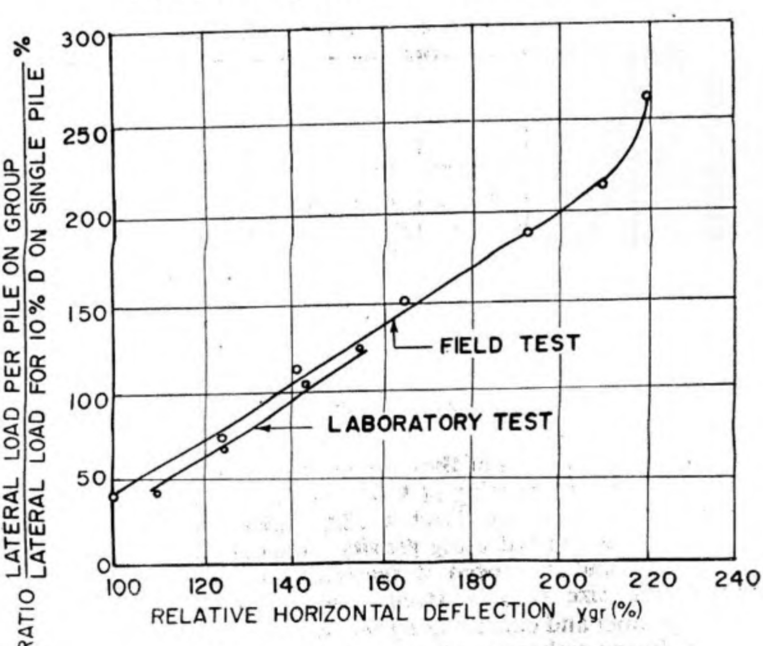

FIGURE 13 : Y_{gr} versus lateral load ratio.

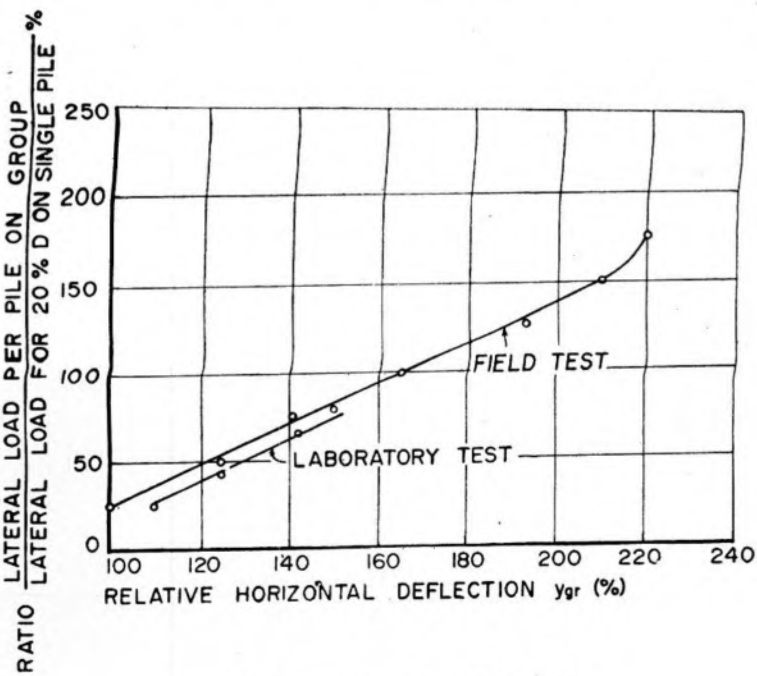

FIGURE 14 : Y_{gr} versus lateral load ratio.

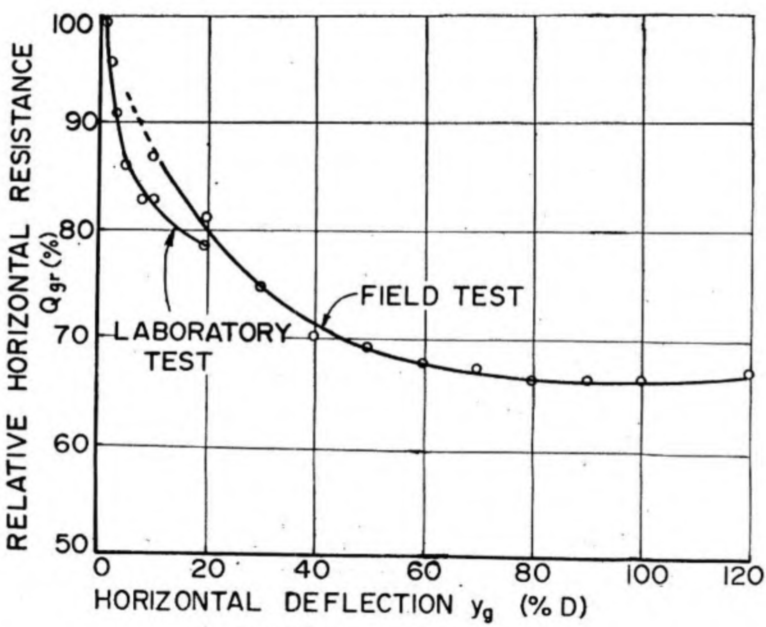

FIGURE 15 : Y_g versus Q_{gr}.

and single pile decreases, the resistance of the group decreasing faster than that of the single pile.

These large scale model tests afforded an opportunity to confirm the validity and utility of laboratory model tests on lateral resistance of piles for predicting the beheviour of actual piles in the field.

List of Symbols

Y_g = Horizontal deflection at ground line.

Y_{gr} = Relative horizontal deflection at ground line.

Q_{gr} = Relative horizontal resistance.

D = Diameter of pile.

EI = Relative stiffness.

References

ASCHENBRENNER, R, (1967) : "Three-dimensional Analysis of Pile Foundations". *Journal of Structural Division, ASCE,* Vol. 93, No. ST1, pp. 201-219, Proceedings paper 5097, New York.

CULMANN, C, (1866) : "Graphische Statik". Zurich. Refer to *Theoretical Soil Mechanics* by K. Terzaghi, John Wiley, 1943.

DAVISSON, M.T. (1960) : "Behaviour of Flexible Vertical Piles subjected to Moment, Shear and Axial Load". *Ph. D. Thesis,* University of Illinois, Urbana.

DAVISSON, M.T. and GILL, H.L. (1963) : "Laterally Loaded Piles in a Layered Soil System". *Journal Soil Mech. and Found. Div., ASCE,* Vol. 89, pp. 63-94.

FEAGIN, L.B. (1937) : "Lateral Pile Loading Tests". *Transactions, ASCE,* Vol. 63, No. 8, Part 2, pp. 236-254, New York.

FEAGIN, L.B. (1953) : "Lateral Load Tests on Groups of Battered and Vertical Piles". *Symposium of Lateral Load Tests on Piles, ASTM Special Technical Publication* No. 154, pp. 12-20, Philadelphia.

GLESER, S.M. (1953) : "Lateral Load Tests on Vertical Fixed-Head and Free-Head Piles". *ASTM Special Technical Publication* No. 154, pp. 75-93, Philadelphia.

HRENNIKOFF, A, (1949) : "Analysis of Pile Foundations with Battered Piles". *Proceedings, ASCE,* Vol. 75, No. 2, pp. 185-208, New York.

MASON, H.G. (1956) : "Field Tests on Laterally Loaded Piles in Sand and Clay". *ASTM Special Technical Publication* No. 206, p. 133.

MATLOCK, H. and REESE, L.C. (1960) : "Generalized Solutions for Laterally Loaded Piles". *Journal of the Soil Mechanics and Foundations Division, ASCE,* Vol. 86, No. SM 5, pp. 63-91, Proceedings paper 2626, New York.

MURTHY, V.N.S. (1964) : "Behaviour of Batter Piles Subjected to Lateral Loads". *Ph. D. Thesis,* Indian Institute of Technology, Kharagpur.

O'HALLORAN, J. (1953): "The Lateral Load Capacity of Timber Pile Groups". *ASTM Special Technical Publication* No. 154, pp. 52-57.

PRAKASH, S. (1962) : "Behaviour of Pile Groups Subjected to Lateral Loads". *Ph. D. Thesis,* University of Illinois, REESE, L.C. and MATLOCK, H. (1956) : "Non-dimensional Solutions for Laterally Loaded Piles with Soil Modulus Assumed Proportional to Depth". *Proceedings Eighth Texas Conference on Soil Mechanics and Foundation Engineering*, Austin, Texas.

SINGH, A. (1969) : "Investigation of Pile Groups under Lateral and Vertical Loads". *Ph. D. Thesis*, University of Jodhpur, Jodhpur.

VESIC, A. (1956) : "Contribution of a l'Etude de Foundations sur Pieux Verticaux et Inclines." *Annales des Travaux Publics de Belgique*, No. 6, pp. 5-77.

VESIC, A.B. (1961): "Beams on Blastic Subgrade and the Winkler's Hypothesis". *Proceedings Fifth International Conference on Soil Mechanics and Foundation Engineering*, Vol. 1, p. 845, Paris.

WAGNER, A.A. (1953) : "Lateral Load Tests on Piles for Design Information". *Special Tech. Pub., ASTEM*, No. 154, pp. 59-72.

WESTERGAARD, H.M. (1917) : "The Resistance of a Group of Piles". *Journal Western Society of Engineers*, Vol. 22, p. 704.

"Unified Soil Classification System for Roads, Airfields, Embankments and Foundations". *Military Standard*, MILSTED-619,—A, March 20, 1962. U.S. Dept. of Defence, Washington-25, D.C.