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

FIELD INSTRUMENTATION OF A DRIVEN PILE
INSTRUMENTATION IN SITU D'UN PIEU BATTU

S. Vaenkatesan

Scientist E II, Geotechnical Engineering Division
Central Building Research Institute
Roorkee, India

SYNOPSIS : The piers of a bridge were to be founded on a group of driven steel pipe piles. The estimated bearing capacity of these piles was counterchecked by separating the point bearing and skin friction through instrumentation. Strain gauges were welded to the inner surface of one pile at seven locations, along the pile length. The pile was subjected to cyclic load test in steps upto the ultimate load. At each step, the load was maintained constant and all the strain gauges were read. The axial loads corresponding to the strain readings, were calculated and analysed. From this it was concluded that when the axial load was small, skin friction formed about 80 % of the total load. As the loading increased, this proportion started falling, and reached a more or less constant value of 65 %, near the ultimate bearing capacity.

INTRODUCTION

Instrumentation provides a direct means of verifying design assumptions and monitoring actual performance of structures. One such "made to measure" scheme was tailored to the needs, and was successful. There were no casualities, all instruments functioned well, each reading had a meaning, and the system provided reliable information. Instrumentation not only served its purpose, but also gave some additional interesting information as detailed here.

The piers of a bridge were to be founded on a group of driven piles. The estimated bearing capacity of these piles was to be counterchecked by two independent means: (i) by conducting a cyclic load test, with measurement of load and settlement by conventional means; (ii) by instrumenting the same pile along its length, and taking readings simultaneously with the cyclic load test. In both cases, it is possible to separate the point bearing and skin friction by different methods. These operations have been carried out on one of the piles below the most critically loaded pier.

Only the instrumentation part is presented in this paper.

AIM

The aim of the present work was to study (through instrumentation) the development of skin friction along the pile length, and to find out the proportion of skin friction to the total load.

SOIL CONDITIONS

At the location of the test pile, the soil strata consisted of soft clay from ground level to about − 17.5 m R.L., with N values 2 to 3 only. Below that, there was a sand layer, whose density increased with depth, categorised as medium dense sand.

PILES

The piles consisted of steel pipes, 812.8 mm. O.D. and 787.4 mm I.D. The bottom of the pipe was to be closed with a flat plate welded around. While driving, the pile would go on compacting the sand till meeting with refusal at about 25 m depth. The working load was 1570 kN.

INSTRUMENTATION SCHEME

In the soft clay layer, no skin friction was expected. Skin friction could develop from near about the clay sand interface, and most of the skin friction and the total point bearing had to come from the medium dense sand layer only. For these reasons, it was decided to locate the instruments mostly in the sand layer, instead of at "equi-distance".

Instruments were placed at seven locations, viz., S1 to S7. S1 was to give the total load on the top of the pile. S2 and S3, located in the soft clay layer, were to give an idea of the small amount of friction developed in that layer and also to give continuous distribution. S4 to S7 were to give the actual distribution of skin friction in the sand layer. The distances between locations S1 to S7 were carefully determined, taking into account thicknesses of different soil layers, as revealed by the bore log.

S7 was located at 80 cm above the pile bottom. By extrapolating the strain distribution curve (S1 ... S7) to the pile bottom, the point bearing could be arrived at. Placing S7 at any lower location would have endangered the instruments while welding the thick bottom plate or while driving. (This consideration ensured no damage to any of the instruments and they functioned in the elastic range.)

STRAIN GAUGE INSTRUMENTATION

Instruments chosen for this was foil resistance strain gauge, that could be spot welded to steel. Since the inside surface of the pile was far safer than the outer surface, it was only a natural choice to weld them to the interior. At each location, four gauges were welded with their lengths parallel to the pile axis.

The gauges and cables were thermally compensated. While S1 was slightly above water table, S2 ... S7 were below it. For these reasons a separate gauge for thermal compensation was not provided. Leads of all 28 strain gauges were anchored to fixtures welded to the pipe so that they would not dangle inside the hollow pile and get damaged while driving. The leads were brought out through a hole below the top, and connected to the strain bridge through a channel selector.

Installation of these instruments was carried out with the pile on the ground, and thoroughly checked before driving the pile. Even heavy driving did not damage the installation.

BASIS OF INTERPRETATION

It is to be noted here that what was directly measured with the help of the strain gauges was only the axial compressive strain at the cylindrical inner surface of the hollow steel pipe pile, superimposed by the effect of any bending. The average of the strain readings measured at the four cardinal points cancel out the effect of any such bending, leaving only the axial strain. From these average strain readings, the axial load at any stage of loading for any location can be readily calculated. The other desired quantities could be simply derived from the actual loads with simple relationships

Axial compressive load at any intermediate station S_i is

$$Q_i = \frac{\pi}{4}(D^2 - d^2) \cdot E \cdot X_i \quad \text{where}$$

D = Outer diameter of the hollow pipe pile
d = Inner diameter of the hollow pipe pile
E = Young's Modulus of steel pipe and
X_i = Measured strain at S_i

With D = 0.812 m, d = 0.787 m, and

E = $200 \cdot 10^{-6}$ kPa, and X being measured in microstrains (i.e.,10^{-6} cm/cm), this relation becomes

$$Q_i = 6.5345 \cdot 10^{-6} \cdot X_i \quad \text{kN}$$

If Q_t denotes the load applied on pile top, the skin friction developed upto S_i

$$= Q_t - Q_i \text{ kN}$$

At the bottom of the pile,

Point bearing = (total load on top) − (skin friction on the total buried length of the pile).

This information can be further analysed on the following principles :

i) At the top section of the pile, the pile material is subjected to an axial stress, which is proportional to the total load applied.

ii) At the bottom section of the pile, the axial stress of the material is proportional to the point bearing of the pile. This will be less than the load applied on top, the difference being due to the skin friction along the buried length of the pile.

iii) At any intermediate section, the axial stress is proportional to the total load on top of the pile, less the skin friction from ground level to that section.

Thus at any stage of loading, the magnitude of skin friction and its distribution along the length of the pile could be arrived at from the measured strain versus the depth curve. For different stages of loading, the development of skin friction and the transmission of point bearing could be studied. From that, the proportion of skin friction to the total load, at any desired level of loading could be deduced.

LOAD TEST

The upper portion of the test pile (from top to 11.2 m) was enclosed in an emptied out casing and was not in contact with the soft clay, to prevent the negative skin friction from affecting the results.

The pile was subjected to cyclic load test as per usual procedure adopted for separating out the point bearing and skin friction. The load was applied on top of the pile by means of hydraulic jacks in steps, upto about 3/4 of the design load and then released, comprising cycle I. Then the step loading was taken upto about twice the design load and then the load released comprising cycle II. This way, the load test was continued further to cycle III about 3 times the design load, and to cycle IV with 3.5 times the design load.

In cycle I, number of steps were 4, (including loading and unloading); in cycle II, 6 ; cycle III, 6 ; and in cycle IV, 5 ; (21 steps in all).

In the conventional test, the applied load was deduced from the pressure gauge of the hydraulic jack and the settlement of the top of the pile was directly read by dial gauges. The readings were later analysed to separate point bearing and skin friction.

In the instrumented test however, settlement observations were not made. Only strain gauge readings were taken, from which the loads were computed. This paper is based entirely on the strain gauge measurements, including the load on the top of the pile.

MEASUREMENTS

Each strain gauge was read individually, directly in microstrain, after accounting for the gauge factor, cable length, initial imbalance, etc. At each step of loading, the load was maintained constant and all the 28 strain gauges were read automatically in sequence and recorded within a short interval, constituting one round of measurement. Like this, 4 rounds were made to ensure repeatability of readings. Thus in all nearly 2500 readings were taken (21 steps x 7 locations x 4 gauges x 4 rounds).

GENERAL OBSERVATIONS

It was gratifying that no strain gauge installation was damaged; and not a single reading was out of the way.

A careful scrutiny of the strain readings shows that at any load step and location, (a) the readings are maximum immediately on application of the load, and diminish with time, coming to a steady value. This is because, as the pile settles, the applied load is somewhat released, the reduction being too small to be seen on the pressure gauge, but faithfully recorded by the more sensitive electronic system. So ignoring such transients, the steady (fourth round) readings were taken for analysis. (b) The strain readings in the four cardinal directions are different from each other, reflecting the combined effects of the eccentricity in seating the jacks, and natural heterogeneity of the soil strata in the horizontal plane, aggravated by driving the pile with bottom closed. (c) The values in any one direction, say A, diminish with depth, and in proportion to that step of loading. So are the cases with the other directions B, C, and D. Hence the average of A, B, C, and D for that location and load step was taken for analysis, eliminating the effects of bending and heterogeneity.

Hereafter strain readings means such averaged out readings.

ANALYSIS OF RESULTS

The strain readings were first plotted to a common axis of elapsed time (Fig.1), and then were plotted against depth (top to bottom) for cycle after cycle, step after step (Figs.2 and 3). Even a cursory glance at the family of graphs shows remarkable consistency in each graph, and cogency from graph to graph, thus confirming the high degree of reliability. The pattern of these family of curves proved that the strain readings followed the logical pattern with respect to all the variables: (1) time (2) space and (3) load.

Fig.1 shows the variation of the strain readings with elapsed time. All the cycles, steps, locations, and loads are clearly discernible without any further explanations.

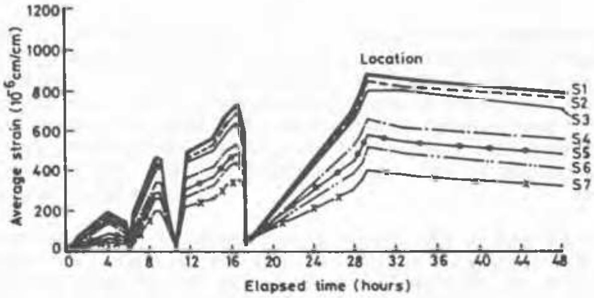

Fig. 1 Variation of strain readings with time

Fig 2. shows the variation of the measured strain with depth, during the first and second cycles of loading for each step. Since the pile was laterally unsupported inside the casing pipe, the strain and load remain constant from the top down to R.L. − 11.2 m. The location of S2 was completely in the soft clay layer, whereas S3 was just above the sand layer.

The development of skin friction from R.L. − 11.2 m to S2 is less, and from S2 to S3 is more. S4 to S7, which are in deeper sandy layers, show development of higher skin friction.

As the loading increases, the curve shifts to the right and as the loading decreases, the curve returns to the left, but not completely, showing a hysterisis similar to the load settlement graph of cyclic load test.

Similarly Fig.3 shows cycles III and IV.

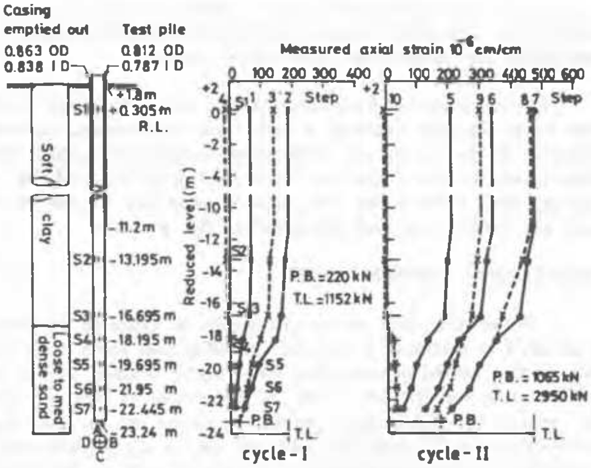

Fig. 2 Strain gauge locations and readings cycles-I and II

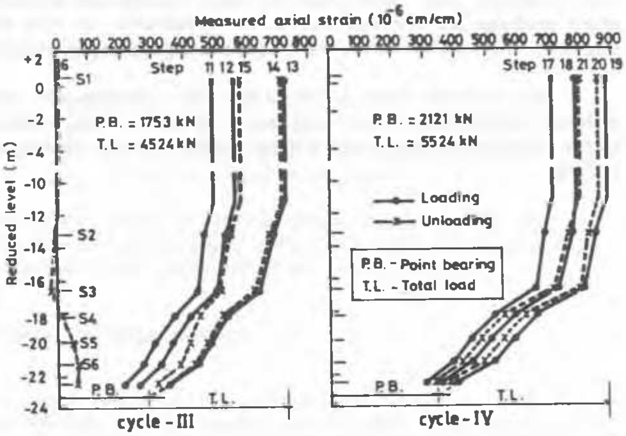

Fig. 3 Strain readings in cycles-III and IV

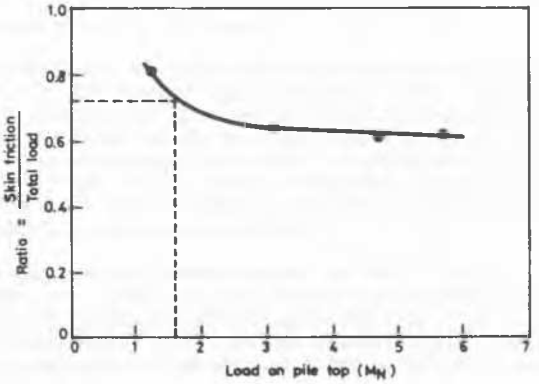

Fig. 4 Proportion of skin friction to total load

All these figures show similar pattern of load distributions with depth. The effect of sand layer in development of skin friction becomes more pronounced with higher cycles.

For working out the proportions of the skin friction to the total loads, the peak loadings of each cycle were chosen. The bottom portions of the curves are extrapolated to meet the pile bottom (Figs.2 and 3), from which the corresponding values of the point bearing, skin friction and the proportions of skin friction to total load are worked out and presented in Fig. 4.

ADDITIONAL INFORMATION

When the load on top of the pile is released and the pile is allowed to rebound, it is quite possible that some parts of the pile in the buried portions may come under tension due to local variations in soil friction. This is discernible in steps 4, 10 and 16, where the distribution graphs go to the left of the Y axis, at locations S4, S3, and S2. But at location S1 which was not subjected to any soil friction due to sleeving, the readings should be zero. The measured average strain at this location S1 for steps 4 and 10 were +18 and +7.5 microstrains indicating some tension. For step 16 it is − 6, indicating some residual compression. This anomaly might have been caused by any inadvertent fixity between pile top and loading frame, or due to some displacement of the hydraulic jack. Neverthless, the loads corresponding to these strain readings are too small to be of significance to the field engineer, but will certainly interest the designer and researcher.

On the other hand, locations S5 to S7 unmistakably show residual compression in the sand layer, giving a visual evidence to the compaction effect that the pile caused during driving and testing.

These fine points are significant, but are missed by conventional load tests. Reasons are obvious. The strain readings are, by far, more sensitive and faithful to the actual load on the pile material than what can be read from the pressure gauge attached to the hydraulic jack. It is even more so, when small loads are attempted to be measured with a robust pressure gauge attached to a high capacity hydraulic jack. The strain gauges have also borne as much load as the piles. And even after that they have not lost their sesitivity or reliability.

CONCLUSIONS

When the axial load was small, (1080 kN at the end of the first cycle) skin friction formed about 80 % of the total load. As the loading increased, this proportion started falling, and reached a more or less constant value of 65 %, near the ultimate bearing capacity.

Instrumentation has not only served the intended purpose, but proved itself as a reliable and sensitive tool by which the functioning of real structures can be evaluated.

ACKNOWLEDGEMENT

This paper reports the work done at the Central Building Research Institute, and the author thanks the Director for permission to publish the same. The assistance provided by Mr. P.C. Rastogi and Mr. Nand Kishore is being gratefully acknowledged.