STUDY OF A VERTICAL PILE UNDER DYNAMIC LATERAL LOAD

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SYNOPSIS

The behaviour of a vertical pile subjected to steady state dynamic loading at the ground level was studied on an aluminium model pile embedded in sand. The load was applied through vibration table which could be excited with known amplitude and frequency of vibration and was measured by proving frame designed for the purpose. A comparison of load deflection has been made with static case.

INTRODUCTION

The use of piles in foundations dates back to prehistoric time. Rows of stakes were used to support primitive structures. Despite its early origin, the settlement of piles under vertical loads during driving were observed for the first time by Perronet in eighteenth century (1). The load displacement of piles loaded laterally was observed for the first time by Sandeman in 1880 (2). Pile foundations used to support structures include vertical as well as battered piles. The loading conditions may be static, cyclic, steady state and transient. A vertically loaded pile has already been analysed theoretically as well as experimentally, to a great extent.

Laterally Loaded Pile :- Large lateral loads act on piles when these are used as support for retaining walls, bridge abutments, piers, fenders, dolphins, anchors for bulkheads and water front and off-shore structures. Figure 1 illustrates two examples of pile supported structures subjected to lateral loads. In Figure 1 a, a retaining wall is subjected to static lateral load, while in Figure 1 b, dynamic lateral load may be acting because of wave action.

Figure 2, illustrates the external loads applied to the pile at ground level, while in Figure 2 b, the loads are applied above the ground level, P represents the vertical loads while M_g and Q_{hg} represent the moment and horizontal shear respectively at the ground surface. M_s represents the moment produced by rotational restraint supplied by the structure and Q_{hs} represents the horizontal shear force when applied above the ground level. Figure 3 a, illustrates the deflected shape of the embedded portion of the pile. The pile has a modulus of elasticity E, moment of inertia I and width B. An approximate soil reaction diagram has also been shown. Figure 3 b, indicates deflection of a pile which can be attributed to rigid body

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[++] Senior Scientific Officer, Central Building Research Institute, Roorkee, formerly, Graduate Student, University of Roorkee, Roorkee. U.P. (INDIA) rotation and its flexural bending.

An investigation of piles subjected to lateral loads involves the study of interaction between the pile and the foundation soil. Most of the analyses of laterally loaded piles involve the concept of modulus of subgrade reaction based on Winkler's (3) assumption, which states that soil strata may be approximated by a series of infinitely, closely spaced independent and elastic springs. Spring stiffness k, known as coefficient of subgrade reaction is defined as

$$k = \frac{w}{y} \qquad - (1)$$

where w = soil reaction at any point and

y = deflection at that point

Soil type and size of loaded area mainly influence k. Terzaghi (4) suggested constant k for piles in over consolidated clays and k linearly varrying with depth for sands

$$k_x = n_h . x \qquad - (2)$$

where k_x = value of k at depth x and

n_h = constant of horizontal subgrade reaction

The problem of laterally loaded piles under static conditions has been studied to a considerable extent by Reese and Matlock (5) and Davisson (6) for k varying linearly with depth. Davisson considered effect of vertical loads also. Prakash (1) investigated the behaviour of pile groups subjected to static lateral loads in sands. Davisson and Gill (7), solved this problem for a constant k for two layered medium.

According to these analyses, the factors governing the displacement of a pile are :-

i) Type of soil

ii) Soil properties i.e. density, moisture content etc.

iii) Variation of soil modulus

iv) Pile properties i.e. pile material, shape, width, length, flexural stiffness etc.

v) Shear and moments etc acting on the pile

vi) Pile end conditions, free or restrained

vii) Method of soil and pile placement and

viii) Relative stiffness factor, defined as

$$T = \sqrt[5]{\frac{EI}{n_h}} \qquad - (3)$$

for linearly varrying k. A non-dimensional depth coefficient

$$Z_{max} = \frac{L_s}{T}. \qquad - (4)$$

where L_s = length of pile

determines the different solutions, which have been presented in the form of non-dimensional curves (5, 6) for $k_x = n_h \cdot x$. A pile is considered rigid if $Z_{max} \leq 2$ and infinitely long if $Z_{max} \geq 5$.

Piles Under Dynamic Lateral Load :- The dynamic lateral loads may be caused because of earthquake and wave action and in machine foundation. Experimental data on actual piles under such loads is difficult to obtain because of cost considerations. Model studies have been reported by Gaul (8), Hayashi and Miyajima (9) and a few others. The information is far from being complete and there is considerable scope for fruitful research in this direction.

In this paper, investigation carried out to study the behaviour of a vertical pile under static and steady state dynamic loads has been reported. Effect of transient dynamic load has been reported elsewhere (10). The lateral load was applied at the ground level on a free head pile. The effect of vertical loads will be included in a subsequent investigation.

The tests were performed on a model aluminium pile 15 mm in outside diameter and 2.5 mm wall thickness. The length of the pile (60 cm) was so chosen that it corresponds to a usual pile length in the field i.e. $Z_{max} \geq 5$. The pile was placed in a steel tank of 60 cms x 30 cm x 61 cm high and sand placed around the pile. The sand was compacted to produce homogeneous soil density.

Steady state dynamic load was applied through a vibration table which could be excited with a known frequency and amplitude of vibration. The load was measured by means of a proving frame on which electric resistance strain gauges were mounted.

A comparison has been made between the behaviour of pile under steady state dynamic and static loads.

PREVIOUS STUDIES

Prakash (11), Davisson (6) and Prakash (1) presented detailed reviews on laterally loaded vertical piles and pile-groups under static conditions only, and will be referred herein only where necessary. The dynamic behaviour of piles will be reviewed in chronological order.

Gaul (8), performed tests on a dimensionally scaled model of a vertical pile under static as well as dynamic loads. The pile was 8 ft. long aluminium pipe 2.375 in. outer diameter and 2.067" inner diameter. Baldwin SR - 4 electric resistance strain gauges were attached at ten locations in diametrically opposite pairs. Montmorillonite rich bentonite was used as soil medium. It had liquid limit of 600 per cent, plastic limit of 50 per cent and moisture content under test conditions of 400 per cent.

The dynamic load was applied by means of a mechanical oscillator. Its magnitude was controlled by adjusting the stroke of the connecting rod. An electronic switching device allowed the simultaneous presentation of a continuous record of the highly amplified strain variations from each channel on an oscilloscope. Records were obtained by time exposure on 35 mm film.

Analysis of the data obtained led him to conclude that :-

1. The pile vibrates in the form of a standing wave which is in phase with the oscillating load.

2. Damping of soil was negligible.

3. At relatively low frequency of load oscillation, the maximum bending moment and the section where it occures are not materially different as compared with a static case.

4. Soil modulus is constant for montmorillonite rich bentonite clay under dynamic load.

This study was done on a special type of clay exhibiting unusual properties. Also, in this investigation, the rate of loading was kept constant at 1 cps. Hence the conclusions stated above cannot be accepted to be generally valid even for clays.

Hayashi and Miyajima (9) conducted tests on vertical steel H - piles embedded in sand and subjected to lateral static and dynamic loads. The piles were 300 x 305 x 15 mm in section and 14 and 16 m long. Tests were performed at four relative densities of sands. Methods of loading were (i) Free vibration of piles caused by the sudden release of initial tension by cutting the wire rope and (ii) forced vibration by the vibration generator installed at the pile head. Bending moment, horizontal displacement of pile head and acceleration were measured. Their findings are :-

1. Natural frequencies and resonance curves of single vertical piles could be calculated by conceiving a simplified system of vibration and the results of calculations agreed with those obtained by the free and forced vibration tests.

2. Damping coefficient measured in the free vibration tests depended on the relative density of the subgrade and the length of free parts of piles.

Matsumoto and Tsuchiya (12) reported lateral load and vibration test data on prototype pile groups consisting of vertical and battered piles. The vibration test was carried out by setting on the monolith or the beam connecting the monoliths, the vibration machine of about 1 ton in weight. Vibration signals were picked up by electromagnetic seismographs registering the motion on a film. Frequencies of the monoliths and single piles were measured. Observing the pulsation of a pile, the predominant period of micro-tremors on the ground was obtained to be about 0.5 and 0.8 seconds in vertical vibrations.

From a perusal of this section it will be observed that very little information is available on this problem. Hence this investigation was undertaken.

EXPERIMENTAL SETUP AND INSTRUMENTATION

General :- The variables involved in the study of single vertical pile subjected to lateral loads have already been enumerated previously. For dynamic study, the frequency and amplitude of loading will also govern the behaviour.

In the investigation under report, a single vertical aluminium pile was embedded in medium sand and static and steady state dynamic loading was applied at the ground level only.

Soil and Pile Properties :- The sand used was medium Ranipur sand (Figure 4) having the following properties :-

a) Dry density γ_d = 1.54 gm/cc (96 lbs/cft)

b) Maximum Void Ratio e_{max} = 0.81

c) Minimum Void Ratio e_{min} = 0.63

d) Void Ratio Under Test e_o = 0.705

e) Relative Density D_R = 0.584

f) Unformity Coefficient U = 1.75

Aluminium pipe section was adopted since strains, and deflections at the same stress are large as compared with those of steel. Other properties of the section are as follows :-

a) Section No. 9442 (ALIND)

b) Outside Diameter 15 mm

c) Wall Thickness	2.5 mm
d) Stiffness EI	13.7 x 10 Kg/cm^2 (4.77 x 10 psi)

For EI determination of the section, two electric resistance strain gauges were bonded to the central section at diametrically opposite ends of a 33 cm long pile and it was subjected to a pure moment. From strain readings corresponding to known moment, EI was calculated. This value was adopted in subsequent computations.

Tank :- The size of the tank is fixed from the following consideration -

i) It should be large enough so that there is no interference of the walls on the behaviour of pile and

ii) It should be small enough so that volume of sand to be handled each time is not too much.

For static tests, it has been shown by Prakash (1) that the interference of one pile does not extend beyond a distance of 8-12 times its width in the direction of loading and 3-4 times its width in the perpendicular direction. However preliminary tests under dynamic loading showed that the zones of influence may extend to a maximum of 30 times the pile width in the direction of and 15 times its width perpendicular to the load. A tank having dimensions 60 cm x 30 cm x 61 cm high was chosen to accomodate even small groups of piles. It was made of mild steel plates 0.33 cm thick with angle iron stiffners at the top and mid height.

Loading Device :-

a) Static loading was applied by means of a string passing over a ball bearing pulley.

b) Steady State dynamic Loading was applied through a horizontal vibration table (13).

The table could be excited with amplitudes of 0.8, 1.77, 2.80, 3.73 and 4.65 mm and at frequency of 0-1000 rpm. The motion of the table does not follow a true sinusoidal path.

Dynamic Load Measurement :- The dynamic load was measured by means of a proving frame on which electric resistance strain gauges had been mounted. It was connected to the shaking table on one side and the pile on the other, by connecting rods, adaptors, and clamps etc. The criterion for design of such a proving frame are as follows (Casagranda and Shannon (14)):-

1. Outside dimensions should be as small as possible but to accomodate strain gauges.

2. The strains at every point should be within the elastic range of the material.

3. The natural frequency of the frame must be more than 20 times the frequency of loading.

A rectangular proving frame was designed using moment distribution method. A 33 cm (13 in) long 1.9 cm (0.75 in) wide and 0.25 cm (0.1 in) thick spring steel strip was bent at three corners and welded at the fourth.

Four Rohit's (India) electric resistance strain gauges of type SA-10 were mounted on three of the four inner sides of the frame (Figure 5). The gauges worked satisfactorily.

Calibration of the Proving Frame :- The proving frame was calibrated both under tension and compression, in three different manners :-

a) Strain (ϵ) as indicated on strain Indicator.

b) Deflection (y_{pf}) of the proving frame from its initial position, measured by a dial gauge having cantilever leg.

c) Number of chart lines (y_{pc}) recorded on a Brush two channel oscillograph.

Calibration with strain was carried out to ascertain the linearity of the frame. Deflection of the proving frame for a known load was required in ascertaining the deflection of the pile and calibration of load versus chart lines was essential to determine the load on the pile. Figure 6, 7 and 8 show load versus ϵ, load versus y_{pf} and load versus y_{pc} for both the tensile and compressive loads. The average shown on the figures were adopted in subsequent computations.

Natural Frequency of Proving Frame :- The proving frame under tension was struck gently with a rod and allowed to vibrate freely. The record of strains indicated a natural frequency of the frame to be close to 175 cps. The maximum frequency of loading was 10 cps. Therefore the natural frequency of the proving frame was about 17.5 times that of load application.

Measurement of Pile Displacement :

a) Static Test :- The displacement of the pile was measured by a dial gauge abutting against a flat connected to the pile at the ground level.

b) Dynamic Test :- Displacement of the pile under dynamic loading was obtained by subtracting the deflection of the proving frame (y_{pf}) from the displacement of the vibration table (y_t), Figure 9. The displacement (amplitude) of the table motion was set at a known value. The deflection of the proving frame was determined with the help of Figures 8 and 7. Figure 10, shows the assembly diagram of tank and pile.

TEST PROCEDURE

Placement of Sand and Pile :- The sand was placed in 10 cm thick layers and each layer was compacted 300 times with the standard proctor hammer. The pile was held in position when the sand was being placed and compacted,

Test Procedure

a) Static Loading :- The load was applied through a loading pan and deflection noted after 5 minutes. The procedure was continued till a load of 40 lbs was applied. The pile was first tested, under a static load before subjecting it to dynamic load.

b) Steady State Dynamic Loading :- The pile was connected to the steady state vibration table through the proving ring Figure 10, and table amplitude of 0.8 mm (1.76 mm peak to peak) was adjusted. The lead wires of the proving frame were connected suitably to the Universal amplifier which was in turn connected to the automatic pen recorder. The table was then excited with frequency increasing from 0-10 cps, and record of load obtained at almost equal increments in frequency. A record at the same frequency was obtained while decreasing the frequency from 10-0 cps.

The pile was then tested under static loads to be followed by a dynamic test at table amplitude of 1.77 mm (i.e. 3.54 mm peak to peak). In this manner six static tests and five dynamic tests were performed.

RESULTS AND DISCUSSION

Figure 11 shows Load versus Displacement (y_g) at the ground surface of all the six static tests.

Figure 12 shows load versus frequency curves for table displacement of 0.8 mm, 1.77 mm, 2.80 mm, 3.73 mm and 4.65 mm respectively. The full lines and points indicate that the frequency is increasing, while the dotted lines stand for decreasing frequency.

Figure 13 shows load versus displacement at G.L. of the pile for frequency of 2, 4, 6, 8 and 10 cycles per second. The static curves at the beginning and at the end are also shown. At any particular frequency, the load was obtained from Figure 12 and displacement was computed from the relationship

$$y_g = y_t - y_{pf} \qquad - (5)$$

where y_g = displacement of pile at ground level.

y_t = table displacement

y_{pf} = deflection of proving frame

The table displacement was known for all the tests. The deflection of the proving frame for a known load was determined from Figure 7. Thus Figure 13 was plotted to study the effect of frequency on the Load displacement of the pile.

It would appear from this figure that the pile becomes stiff as frequency increases. Also it shows smaller displacement under a dynamic load than under a static load intially. It is however, important to note that when the pile is vibrated at a fixed table displacement the load varies, usually increasing with increase in frequency as evidenced from Figure 12. The change in load could be a manifestation of both the increase in density of sand due to compaction and due to rate of loading. For the same table displacements at greater load, the deflection of the proving frame increases, resulting in smaller displacement of the pile (Equation 5). In order to study this phenomenon and to separate the two effects stated above, Figure 14 was plotted. In this figure curves A, B, C, D, and E represent the load versus displacement in the dynamic test at table displacements of 0.8 mm, 1.77 mm, 2.80 mm, 3.73 mm and 4.65 mm respectively. The frequency interval plotted is from 2 to 10 cps. Corresponding static test data after each dynamic test is shown by curves a, b, c, d and e respectively. These curves are displaced up from the initial load-displacement curve, because vibration of the pile causes compaction. The difference between curve b and a is larger than that between c and b . And the difference between e and d is very small. This indicates that compaction of the soil takes place to a larger degree first and with increase in amplitide of vibration, it tends to reach an optimum value.

Curve a and b are lower than curves A and B respectively indicating that effect of compaction during vibration is more predominant. Curves C , D and E are lower than curves c , d and e, which are for static case, indicating that the effect of rate of loading is predominant. The static strength immediately after the dynamic test is considerably greater than the corresponding dynamic strength especially in case e and E . For a load of approximately 40 lbs, the displacement under steady state vibratory load is 2.26 mm, while under static load it is 1.65 mm.

Only one point for E also indicates that there is no effect of compaction as is evident in curves A, B, C and D. Similar results were obtained when the load was applied above the ground level. Thus it would appear that effect of dynamic loading is to make the pile-soil system less stiff while the change in the frequency of loading has no effect, within the range of frequencies of these tests. These findings are usually in conformity with concepts of strength of soils under vibratory loading.

Damping of Soil-Pile System :- The natural frequency of the soil-pile system was measured by a CEC displacement pick-up. This afforded an opportunity to calculate the damping of system from the expression :-

$$\delta = \frac{2\pi\xi}{\sqrt{1-\xi^2}} = \frac{1}{k} \log_e \frac{X_m}{X_{m+k}} \qquad - (6)$$

where δ = logarithmic decrement

ξ = damping factor

X_m = measured amplitude at mth cycle = 13.5 for m = 1

X_{m+k} = measured amplitude at (m + k) th cycle = 1.5 for m + k = 12 which gives ξ = 3.18%

CONCLUSIONS

1. Under steady state dynamic loading, the soil around the pile gets compacted, initially to a large extent till optimum compaction is reached.
2. The initial static strength of a pile is less than the steady state dynamic strength. But after the soil gets compacted to a large degree, the static strength is larger than the dynamic strength.
3. The zone of influence of a dynamically loaded pile extends to a considerably greater distance than that for a statically loaded pile.
4. The damping of the soil-pile system is about 3 per cent.

ACKNOELEDGEMENT

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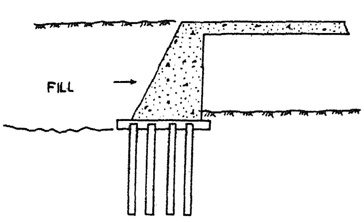
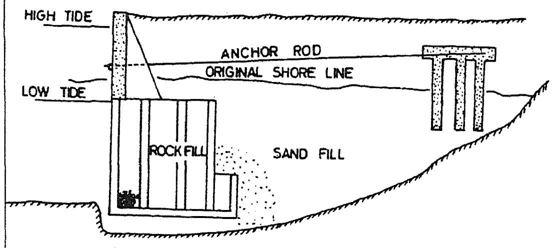
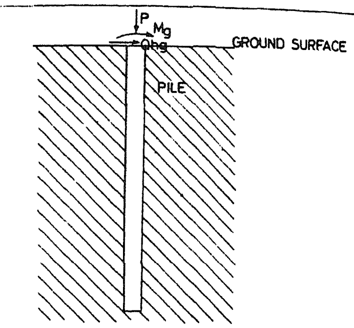


(a) RETAINING WALL

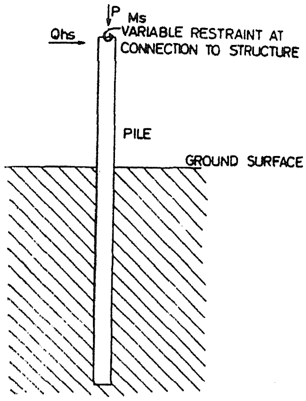


(b) WATER FRONT STRUCTURE

FIG.1- LATERALLY LOADED PILES

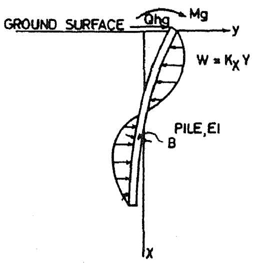


(a) LOAD APPLIED AT GROUND LINE

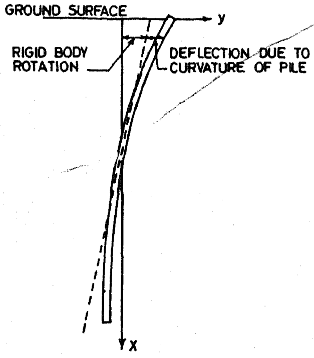


(b) LOAD APPLIED ABOVE GROUND LINE

FIG. 2 - EXTERNAL LOADS APPLIED TO PILE



(a) FORCE SYSTEM AND DEFLECTED SHAPE OF PILE



(b) DEFLECTION OF PILE

FIG.3-SYSTEM OF FORCES AND DEFLECTED SHAPE OF PILE

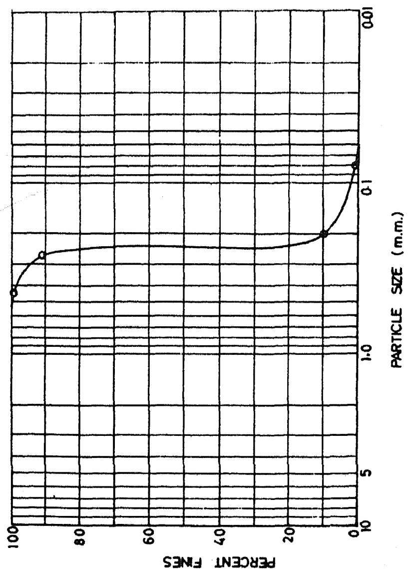


FIG.4- GRAIN SIZE DISTRIBUTION

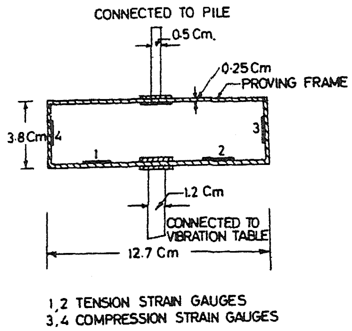


FIG. 5 - PROVING FRAME

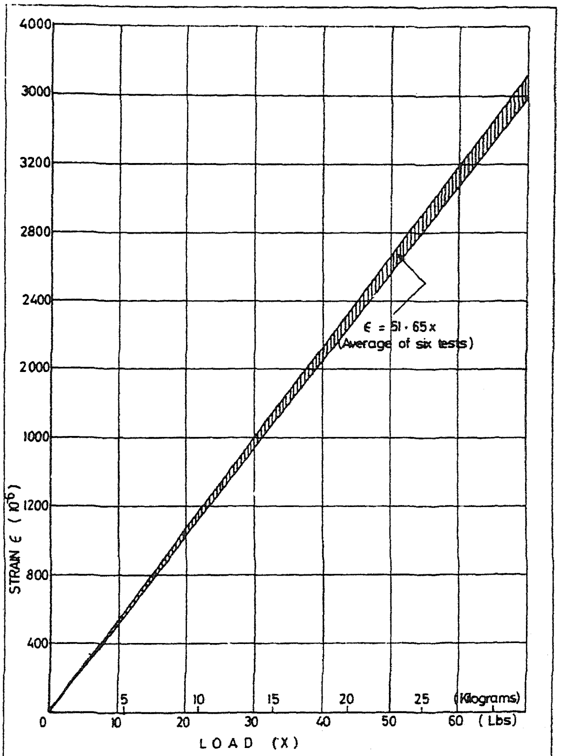


FIG.6.CALIBRATION CURVE OF PROVING FRAME FOR STRAIN

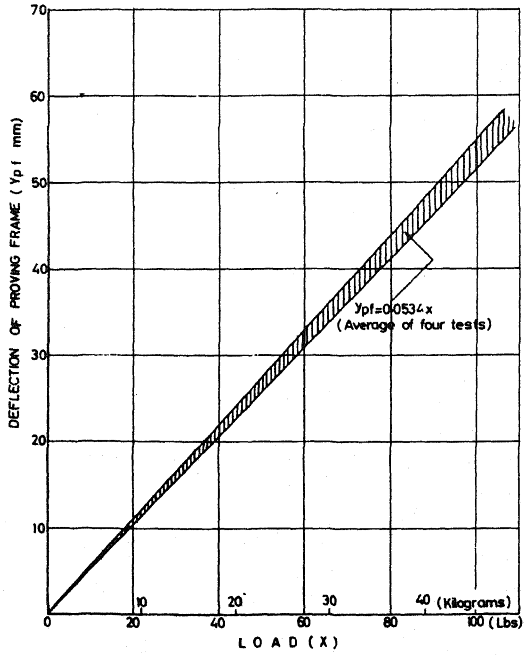


FIG. 7.CALIBRATION OF PROVING FRAME FOR DFFLECTION

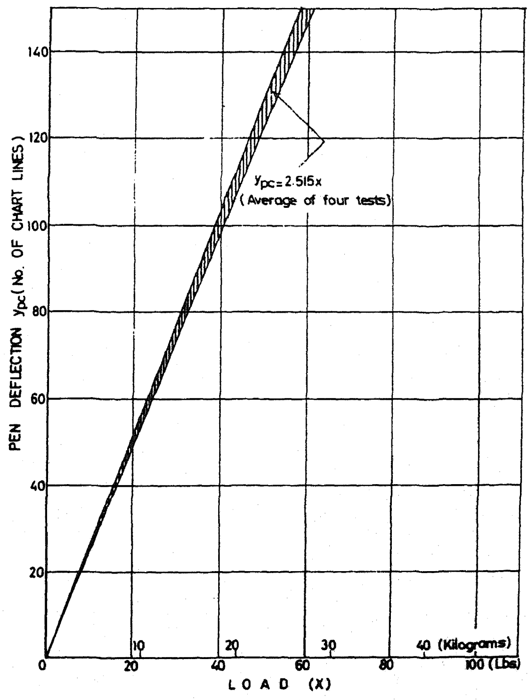


FIG. 8. CALIBRATION OF PROVING FRAME FOR PEN DEFLECTION

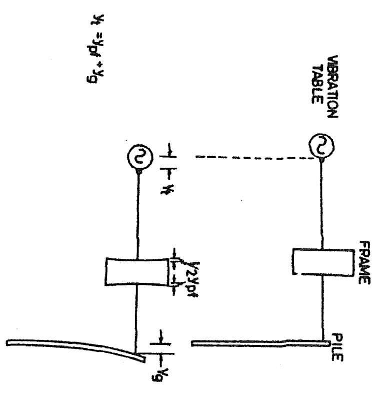


FIG.9 _METHOD OF DETERMINING PILE DISPLACEMENT(y_g)

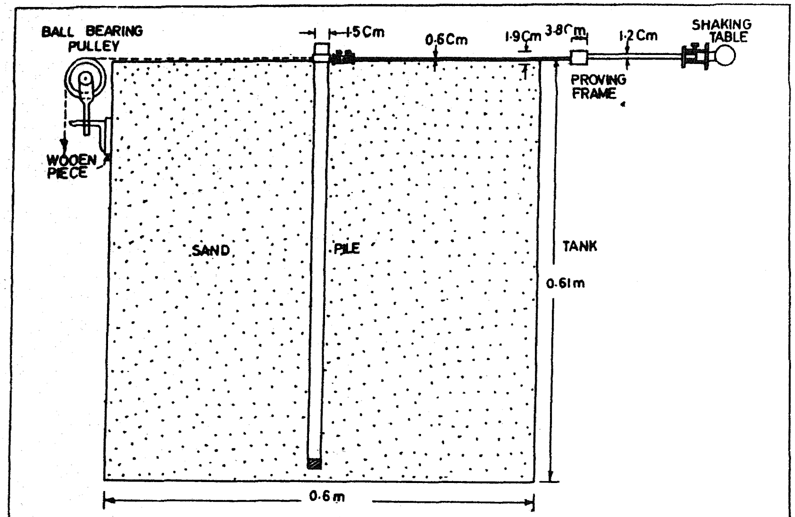


FIG.10 _PILE TANK ASSEMBLY WITH NECESSARY CONNECTIONS

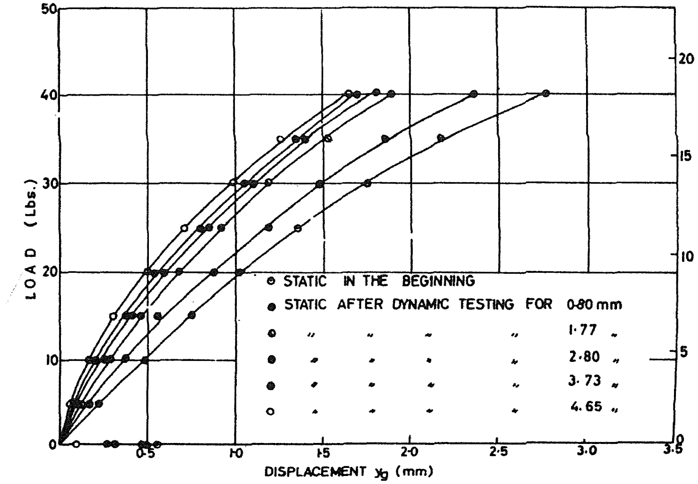


FIG.11_LOAD Vs. DISPLACEMENT (Yg) UNDER STATIC LOADS WITH LOAD AT G.L.

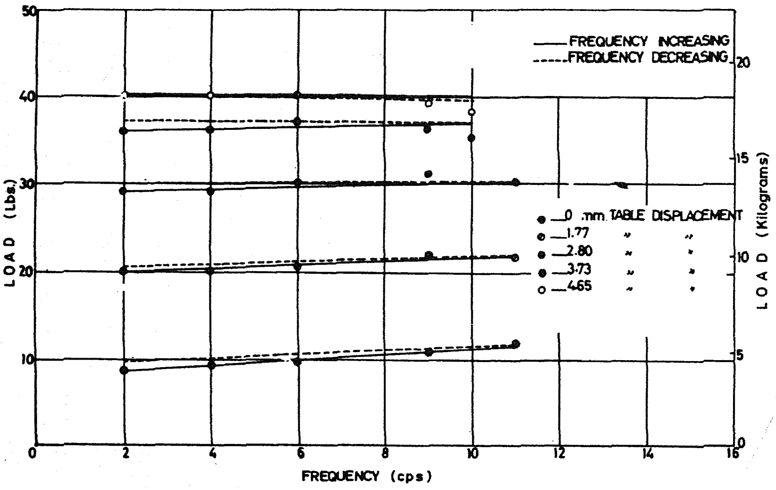


FIG.12_LOAD FREQUENCY CURVE (WITH LOAD AT G.L.)

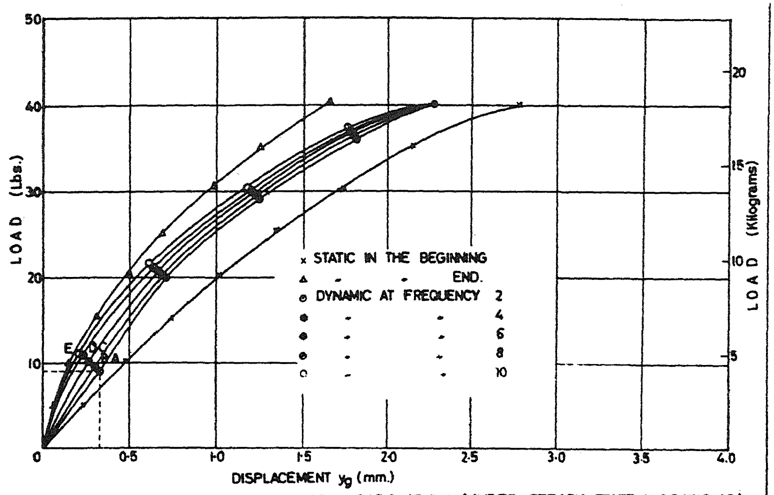


FIG.13_LOAD DISPLACEMENT CURVES WITH LOADS AT G.L.(UNDER STEADY STATE VIBRATIONS)

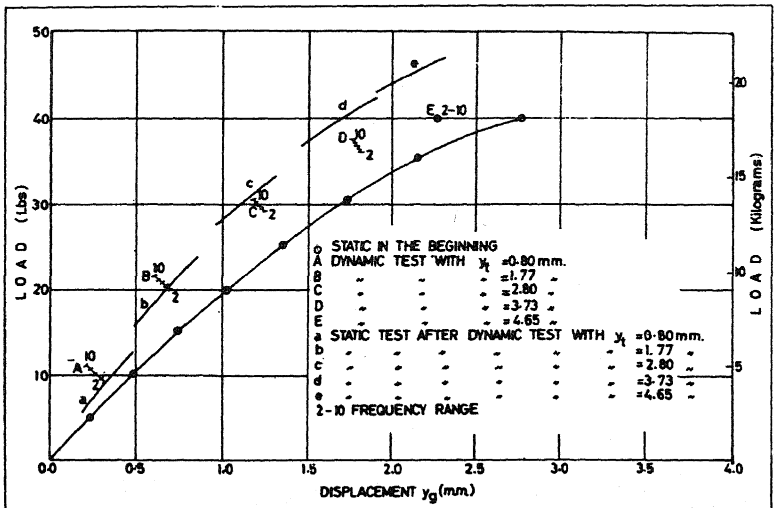


FIG.14_LOAD DISPLACEMENT CURVES UNDER STATIC AND DYNAMIC LOADS