Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-1951

Static and dynamic bending behaviour of piles in clay

Comportement de recourbement statique et dynamique des piles en argile

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ABSTRACT

Static and dynamic lateral load tests were carried out on the model aluminium single piles embedded in soft clay to investigate the bending behaviour of piles. Piles with different length to diameter ratio were subjected to static lateral load and steady state harmonic vibrations with different magnitudes of load and wide range of frequencies. The load transferred to the pile, pile head displacement and the strain variation along the length of pile were observed and measured using a Data Acquisition System. The displacement amplitude under dynamic load is magnified by about 2 times the static deflection. The maximum dynamic bending moment is magnified by about 3 to 5 times the maximum static bending moment for piles tested. The maximum dynamic bending moment occurs at a depth of about 2 times the depth of occurrence of maximum static bending moment.

RÉSUMÉ

Des essais latéraux statiques et dynamiques de charge ont été effectués sur les piles simples d'aluminium modèle incorporées en argile mol pour étudier le comportement de recourbement des piles. Des piles avec la longueur différente au rapport de diamètre ont été soumises aux vibrations harmoniques de charge latérale statique et d'état d'équilibre avec différentes importances de charge et d'éventail de fréquences. La charge transférée à la pile, le déplacement principal de pile et la variation de contrainte sur la longueur de la pile ont été observés et mesurés employer un système d'acquisition de données. L'amplitude de déplacement sous la charge dynamique est magnifiée par environ 2 fois le débattement statique. Le moment de flexion dynamique maximum est magnifié par environ 3 à 5 fois où le moment de flexion statique maximum pour des piles a examinees. Le moment de flexion dynamique maximum se produit à une profondeur d'environ 2 fois la profondeur de l'occurrence du moment de flexion statique maximum.

1 INTRODUCTION

Piles are commonly employed in loose sand and soft clay deposits to support machines for power plants, petrochemical complexes and compressor stations and multi-storeyed buildings. These piles are subjected to dynamic lateral loads resulting from operating machines, wind, ocean waves and earthquakes in addition to the static lateral loads. Design of piles to resist lateral loads is primarily based on the limiting deflection criteria considering the safe operation of the superstructure. Consequently, a careful engineering analysis of lateral pile deflections under anticipated static and dynamic working loads becomes crucial step in the satisfactory design and performance of piles.

Poulos and Davis (1980) gave comprehensive collections of solutions for the design of piles to resist static lateral loads. In the last few decades, significant research has been undertaken on understanding the fundamental characteristics of piles under dynamic lateral loads. Among various approaches, Novak's Continuum Approach (Novak, 1974) is widely used in practice for dynamic analysis of piles, which assumed linear behaviour of soil. However, the field investigation carried out by various authors (Puri and Prakash, 1992 and Boominathan et al. 2002) show large discrepancy between observed and estimated values due to nonlinear behaviour of soil and gapping at the pile-soil interface. Kuhlemeyer (1979) is one of those who firstly attempted the dynamic soil - pile interaction problem adopting the finite element method, which is very intensive and expensive. In recent years, Nogami et al. (1992), Kavvadas and Gazetas (1993), Badoni and Makris (1996), El Naggar and Novak (1996) and Han (2002) developed models by approximately accounting for the nonlinear behaviour of soil.

Literature on the experimental studies exclusively on model piles embedded in clays under lateral dynamic loads and parametric studies are very limited (Agarwal, 1973: Novak and Grigg, 1976). The active pile length is an important parameter in the lateral load analysis of pile (Konagai, 2004) and the effects of soil – pile parameters on the active pile length under dynamic load are not clearly understood yet. This paper discussed the results of experimental investigation carried out on single piles embedded in the soft clay subjected to both static and dynamic lateral loads.

2 MATERIALS

2.1 Soil

Clay sample was collected from the Chennai city (India) used in the present investigation. The index and engineering properties were determined by carrying out laboratory tests on soil samples and results are presented in Table 1. The soil is classified as CH clay as per IS: 1498 – 1987.

Table 1. Properties of clay

Gravel, %	1.0
Sand, %	25.0
Silt, %	32.5
Clay, %	41.5
Liquid limit, %	74.0
Plastic limit, %	26.0
Plasticity index, %	48.0
Shear strength, S_u, kN/m^2 at $I_c = 0.15$	9.3

2.2 Pile

Aluminum model piles with an outer diameter of 25 mm and thickness of 3 mm were used. The length to diameter ratio

(L/d) of the pile was selected as 10 to 40 to cover the behaviour of both short rigid piles and long flexible piles based on the relative stiffness of the soil – pile system. A conical driving shoe was fixed at the pile tip to enhance driving and to prevent soil plugging. Piles were also instrumented with foil type electrical strain gauges length to study its bending behaviour (Fig. 1). The instrumented model pile is calibrated for strain gauges by simple bending test with simply supported conditions. A pile cap of mass equals to 3.1 N is attached to the pile head to simulate clear resonance condition of piles.

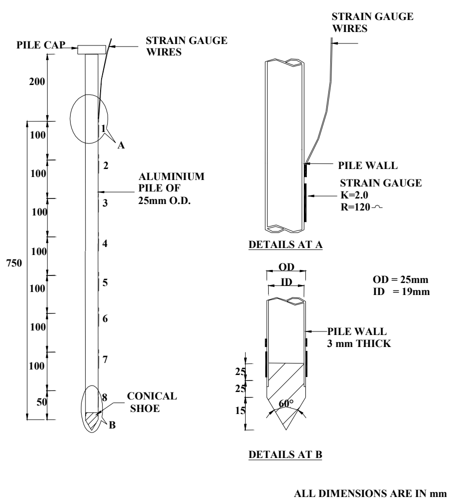

Figure 1. Instrumented model pile.

3 EXPERIMENTAL SETUP

3.1 *Static Test*

The plan dimensions of the test facility are normally decided based on the effectively stressed zone of soil mass from the pile. It is 10 times the diameter of the pile in the direction of loading for piles under static lateral loads (Narasimha Rao et al. 1998). Hence, the static lateral load tests are conducted in a test tank having a circular cross-section of diameter 600 mm and height 1200 mm placed on a loading platform. The static lateral load is applied by means of dead weights placed on a hanger connected to a flexible steel wire, strung over a pulley supported by a loading platform.

3.2 *Dynamic Test*

In the case of dynamic loading, the size of the test tank is decided based on the reflection of vibration induced-stress waves from the boundary of tank wall. To have minimum wave reflection, the Elastic Half Space Simulation (EHSS) has been made as adopted by Stokoe and Woods (1972) is shown in Fig. 2. The simulated EHSS facility consists of a test tank of size 2.0 x 2.0 x 1.5 m, an absorbing layer of saw dust and a boundary element between them. The tank wall is made of hollow cement blocks of about 250 mm thickness. The boundary element consists of a mild steel basket in logarithmic arc spiral shape, which is covered with the geomembrane sheet to separate the soil from the absorbing layer as well as to maintain constant moisture content in the clay layer. The geomembrane is made to the required logarithmic arc shape with the mild steel basket by hot air welding. After welding, fiberglass coating is applied to bond the mild steel basket with welded geomembrane.

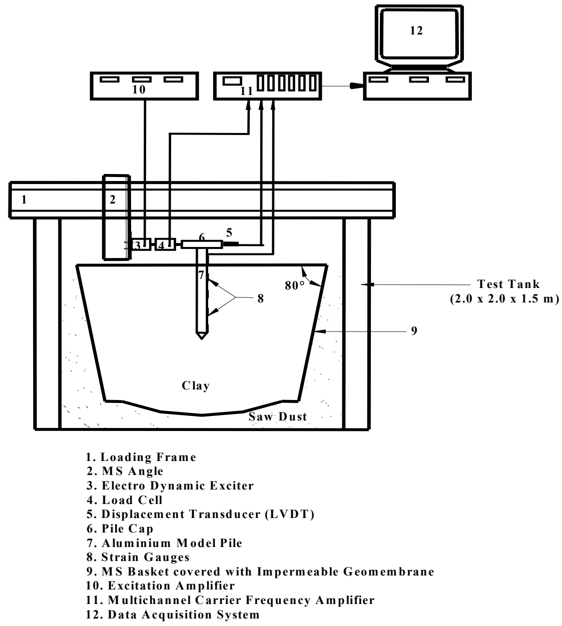

Figure 2. Simulated Elastic Half Space – Dynamic test setup.

4 INSTRUMENTATION AND MEASUREMENT

Static lateral load was applied by rope and pulley arrangement. A 100 N-capacity electro dynamic exciter applied steady state sinusoidal dynamic lateral excitation. A HBM make 2 kN capacity load cell attached between the pile cap and rope/exciter was used to measure the load transferred to the pile and the LVDT fixed on the pile cap was used to measure the pile head displacement (Fig. 2). Two dial gauges; one fixed close to the surface of soil and another fixed close to the pile head measured the static pile head deflection. The instrumented model pile measured the bending moment along the pile length under static and dynamic lateral loads. A Data Acquisition System consisting of Pentium II PC with DAS card, DAS software “GeniDAQ” and HBM make MGC plus multi-channel digital carrier frequency amplifier system was used to observe and measure the load transferred to the pile head, pile head displacement and strain along the pile length automatically.

5 TEST PROCEDURE

5.1 *Clay Bed Preparation And Pile Installation*

Clay was mixed with water to get the consistency index of 0.15. Uniformly mixed clay was placed and hand-packed in the test tank in several layers of 15 cm thickness and was tamped with template to remove the entrapped air, if any. The clay was filled upto a maximum depth of 1.2 m both in the EHSS and the static test tank. The water content was determined on the soil samples collected from various depths of soil bed and found that the water content was almost constant with depth, which ensured the homogeneity of the clay bed. The cross-hole tests were conducted in EHSS to determine the shear wave velocity of clay. The shear wave velocity and calculated maximum shear modulus of clay are presented in Table 2. The instrumented model pile was then installed into the prepared clay bed by gently pushing it vertically. Sufficient time was allowed for the clay to regain its original shear strength before commencing the tests, which depends on the degree of disturbance during pile installation and thixotropic nature of the clay.

Table 2. Dynamic properties of clay

Depth m	Density (ρ) kN / m^3	Shear wave velocity (V_s) m/s	Dynamic shear modulus (G_{max}) kN/m^2
0.25	20.65	59.27	6586.75
0.50	20.38	60.28	6784.08
0.75	20.13	60.31	6921.41
1.00	20.64	60.14	6843.12

5.2 Static Test

The static lateral load tests were conducted as per IS: 2911 (Part 4) – 1985. The pile deflection and strains along the pile length were measured for each increment of load using the DAS described above. The tests were conducted on piles with length to diameter ratios (L/d) of 10, 20, 30 and 40, embedded in soft clay.

5.3 Dynamic Test

The steady state sinusoidal vibration of different magnitudes of load and frequency was applied to the pile head. The load transferred to the pile head, pile head displacement and dynamic strain along the length of pile are observed and measured using the DAS. Dynamic experiments were conducted for different magnitudes of lateral dynamic load (F_o) of 7 N, 14 N, 21 N and 30 N applied at wide range of frequency of excitation (f) from 2 Hz to 50 Hz.

6 RESULTS AND DISCUSSION

6.1 Static Response of Piles

A typical load - deflection curve upto a load equal to the maximum dynamic load applied for piles embedded in soft clay is shown in Fig 4. It is observed from Fig. 4 that the deflection occurs steadily with the applied lateral load for all piles within the load range shown in the figure.

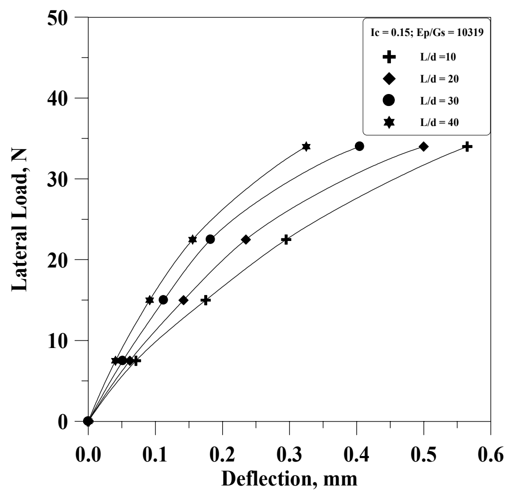

Figure 4. Load – deflection curve for different pile length.

The variation of static bending moment (BM) along the length of pile for L/d = 10 is shown in Fig. 5. The figure indicates that the maximum bending moment occurs at a depth of about 5 times the pile diameter from the ground level. The depth of maximum bending moment for all piles embedded at the consistency index, 0.15 ranges from 5 to 10 times the pile diameter.

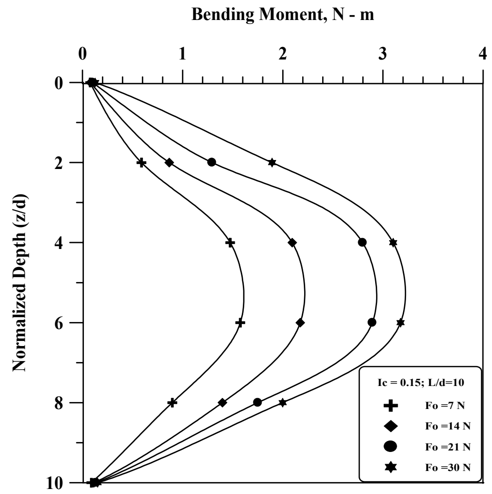

Figure 5. Variation of static bending moment with normalized depth for pile with L/d = 10.

6.2 Dynamic Response of Piles

The dynamic magnification factor (DMF), i.e. the ratio of dynamic pile head displacement amplitude to the static pile deflection at each load level was evaluated and a typical variation of DMF with frequency for pile with L/d = 20 is given in Fig. 6. It could be inferred from the figure that the peak amplitude is magnified by about 1.3 to 1.7 times at low magnitudes of applied load (F_o = 7 N & 14 N). But at relatively higher magnitudes of applied load (F_o = 21 N & 30 N), the magnification factor is only about 0.7 to 0.9. This is mainly because of the reduction of dynamic amplitude due to increase of hysteretic damping at higher magnitude of applied dynamic loads. The similar trend is observed with all piles tested.

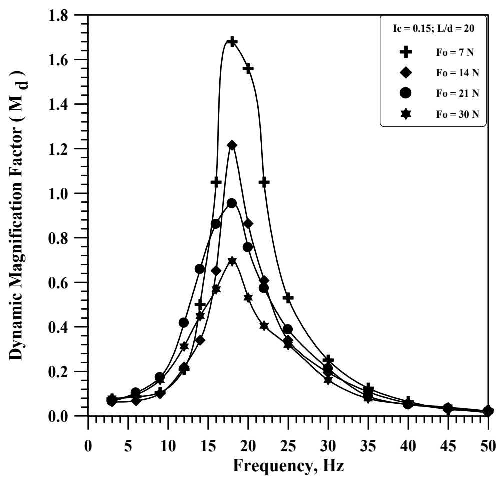

Figure 6. Dynamic magnification factor vs. frequency (L/d = 20).

It is observed from the results that the bending moment reaches maximum at the fundamental frequency of the soil – pile system due to large inertial force mobilized near resonance region (Ayothiraman and Boominathan, 2004). The variation of dynamic bending moment with normalized depth for pile with L/d = 20 is shown in Fig. 7. It is inferred from Fig. 7 that the dynamic bending moment towards the pile tip does not reach zero, which indicates that, even the lower parts of the pile affect the pile head response to the inertia loads applied at the pile head. The depth of maximum BM measured under both static and dynamic loads are given in Table 3. The table clearly depicts that the depth of maximum BM under dynamic load is about 2 times higher than that the static case. This indicates that the active pile length is high for dynamic load that necessitates the additional pile length required under dynamic load.

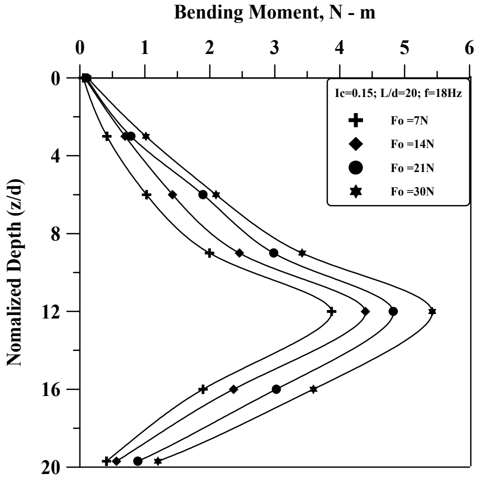

Figure 7. Variation of dynamic bending moment with normalized depth for pile with L/d = 20.

Table 3. Depth of maximum BM

L/d	Depth of Maximum BM	
	Static	Dynamic
10	5 d	10 d
20	6 d	12 d
30	8 d	18 d
40	10 d	19 d

The variation of the maximum BM ratio, i.e. the ratio of maximum dynamic BM to the maximum static BM with pile length is shown in Fig. 8. The figure shows that the maximum dynamic BM is magnified by about 2 times the maximum static BM for short piles (L/d ≤ 20). For long piles (L/d = 30 and 40), the maximum dynamic BM is magnified significantly by about 3 to 4 times the static BM. It is due to the fact that a larger passive resistance and inertial force are mobilized along the increased active length of the pile under dynamic loads.

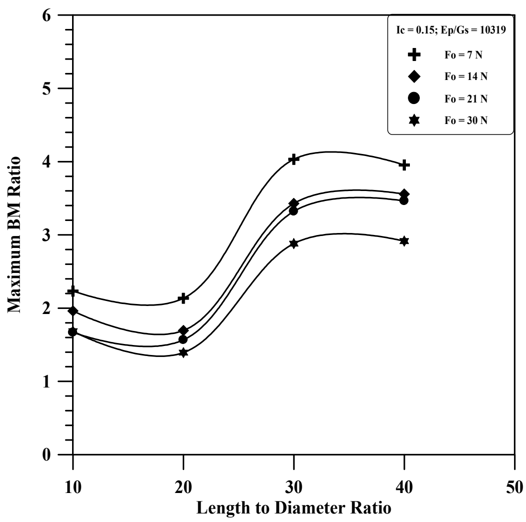

Figure 8. Variation of maximum BM ratio with pile length.

7 CONCLUSIONS

Based on the experimental studies carried out on model single piles embedded in soft clay soil subjected to static and dynamic lateral loads, it is found that within the range of magnitudes of applied load, the resonant amplitude under dynamic load is magnified by about 2 times the static deflection. The maximum dynamic bending moment of pile is magnified by about 2 to 4 times the maximum static bending moment for short and long piles respectively. The active pile length under dynamic loads increases by about 2 times that necessitates the additional pile length required under dynamic load.

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