Bearing Capacity Analysis of Flexible Batter Piles in Sand and Clay Under Horizontal Loads

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Abstract.
In view of the frequent applications of batter piles in foundation to resists lateral loads, a considerable amount of theoretical work has been done besides field and laboratory tests to evaluate the performance of such piles. However, it is generally difficult to read the ultimate bearing capacity of flexible batter piles under horizontal loads from load ~ deflection curves. In this paper, the fitting method is introduced to determine the ultimate bearing capacity of flexible batter piles in homogeneous sand and in clay under horizontal loads and its applicability is discussed experimentally. Model tests were carried out using instrumented flexible piles of wide-ranging flexibilities. Bearing capacity of flexible batter piles in sand and clay was conducted separately. In the sand case piles were buried in loose, medium and dense sand. In the clay case piles were pushed into clay. Piles were installed at batter angles β= 0°, ±15° and ±30° and were subjected to incrementally increasing horizontal loads. Reasonable agreement was found between the present theory of ultimate bearing capacity and the theory of Meyerhof and Ranjan (1973). The present theory was applied to 2 (two) group of piles at batter angels β= 0°, ±15° and ±30° in sand and clay. The result was shown good agreement between present theory and ultimate bearing capacity of pile group.

Key Words: batter pile, bearing capacity, clay, horizontal load, model test.

1. Introduction

Batter piles are usually employed when the lateral load exceeds an allowable limit for vertical piles (Peck et al., 1953; McNulty, 1956) and widely used to support lateral loads caused on the foundation of many civil engineering constructions such as bridge abutments, transmission towers, offshore structures and quay walls. Recent review of analyses of laterally loaded piles of various stiffness in homogeneous elastic soils indicates (Meyerhof, 1979b; Meyerhof and Yalcin, 1984) that free head piles may be considered rigid for practical purposes if their relative stiffness $K_r \geq 0.01$ and flexible piles if their relative stiffness $K_r \leq 0.01$. An out batter or a positive batter pile has horizontal load acting in the opposite direction to the batter, while a negative batter pile has horizontal load acting in the same direction of the batter.

Earlier extensive theoretical and experimental studies have been made in the past to analyze the behaviour of single vertical and batter piles in various soils under various loads. For example, (Tschebotarioff, 1953; Murthy, 1964; Brinch Hansen, 1961; Kubo, 1965; Awad and Petrasovids, 1968; Chin, 1970; Poulos and Davis, 1980; Meyerhof and Ranjan, 1973; Meyerhof, 1981; Meyerhof et al., 1981; Takahashi Kunio, 1985). More recently, behaviour of batter piles under inclined loads in layered soil (Meyerhof and Yalcin, 1993) was among the contributions based on this experimental work. Lately, bearing capacity and deflection of laterally loaded flexible piles was given by Sastry, Koumoto and Manoppo (1995).

A wide variety of criteria for interpreting loading tests results have been made. However, no attempts seem to have been made in the past to study how to determine the ultimate bearing capacity of loading tests results in the case of flexible batter piles under horizontal loads. One of

the problems is the difficulty to determine theoretically the ultimate bearing capacity at local shear failure type III.

Whereas most of the loading test results in the present investigations are closed to type III, the Terzaghi (1967) method was available until type II. The purpose of this paper is to propose the fitting method and introduce the factor m for determining the ultimate bearing capacity of loading tests results load Q and deflection Y curves.

2. Model Test

2.1. Soil and Pile Data

Sands used in the test was uniformly graded having effective size = 0.12 mm and uniformity coefficient = 1.67. The minimum and maximum void ratios of the sand were 0.61 and 0.96, respectively and the porosity of 47% gave a unit weight of about 14.0 kN/m^3 and the friction angle ϕ=31.0^0 (Koumoto and Kaku, 1988). Based on the above test, for unit weight 15.0 kN/m^3 and unit weight 15.5 kN/m^3 were given friction angle ϕ=37.0^0 and friction angle ϕ=39.2^0. Assuming isotropy, the values of horizontal modulus elasticity of soil E_s along the embedded length of pile was back calculated from vertical rigid pile tests burried in the same sand. The value of E_s was zero at the ground level, and was linearly increasing to a value of 365.000 kN/m^2 at a depth of 380 mm. Based on that test the values of E_s at unit weight 15.0 kN/m^3 and 15.5 kN/m^3 are 761.215 kN/m^2 and 1376.365 kN/m^2.

Clay used in the test had natural water content of 133.05%, liquid limit of 126.60% and plastic limit of 64.97%. The clay was then packed and compacted by kneading into test box. The modulus elasticity of clay was 90.60 kN/m^2. The average undrained shear strength C_u was 1.51 kN/m^2. The model piles were made of alumunium, acrylic, hard rubber pipes and steel having an outside diameter B of about 16 mm, 30 mm, 40 mm and wall thickness of 1 to 4 mm. Twelve piles were used for sand and eight piles for clay. The piles were buried to the length L of 160 mm, 320 mm, 380 mm, 400 mm, 600mm and 640 mm in sand case and pushed for clay case. The relative pile stiffness K_r ranged from 69×10^{-1} to10^{-5}.

2.2. Test Details

Sand was rained and compacted in a square tank 48 ×48 cm and 80 cm depth. When the soil surface reached the required level, the pile was placed at a required batter angle $\beta = 0^0$, $\pm15^0$ and $\pm30^0$ to the vertical. The raining was continued until the tank was full. The horizontal load was applied in 10 to 20 increments, each being 0.0005 to 0.0200 kN depending on the estimated failure load. The load was applied 20.0 mm and 25.4 mm above the ground level, through a wire passing over a pulley and attached to the pile top. The horizontal deflection of the load point was measured by a LVDT (Linear Voltage Differential Transducer). The gauge outputs under a given load were recorded by using Logger Mate DL 1200.

The clay was then packed and compacted by kneading into test boxes, wrapped with a plastic cover to prevent the escape of moisture, the pile was pushed at a required batter angle $\beta = 0^0$, $\pm15^0$ and $\pm30^0$. The horizontal load was applied and the horizontal deflection of the load point was measured by a LVDT. The loading tests results load Q and deflection Y curves are being presented typically in Fig.1.
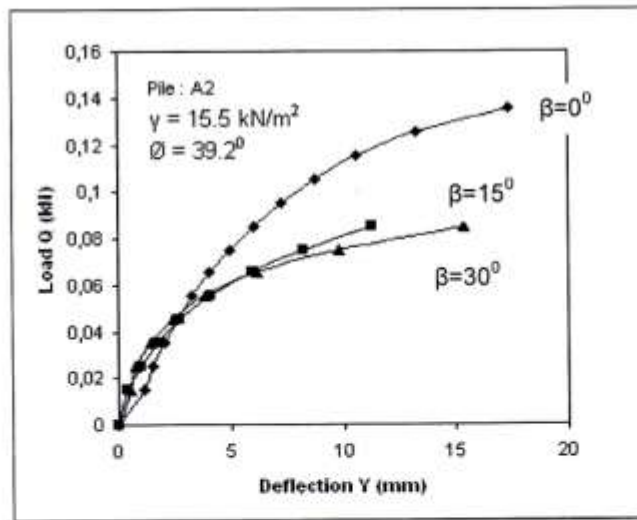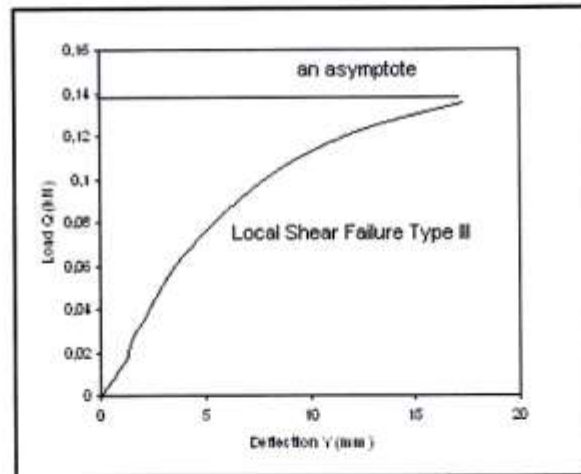
**Figure 1** Typical load Q and deflection Y curves at various angle of piles

3. Analysis of Results

The fitting method is used to estimate the ultimate bearing capacity of the piles loading tests results, assuming the ultimate bearing capacity Q_u is an asymptote as shown in Fig.2.

Figure 2 Assumption of ultimate bearing capacity of pile loading test

The loading tests results load Q and deflection Y curves can be transformed to be deflection Y divided load Q versus deflection Y curves as shown typically in Fig.3
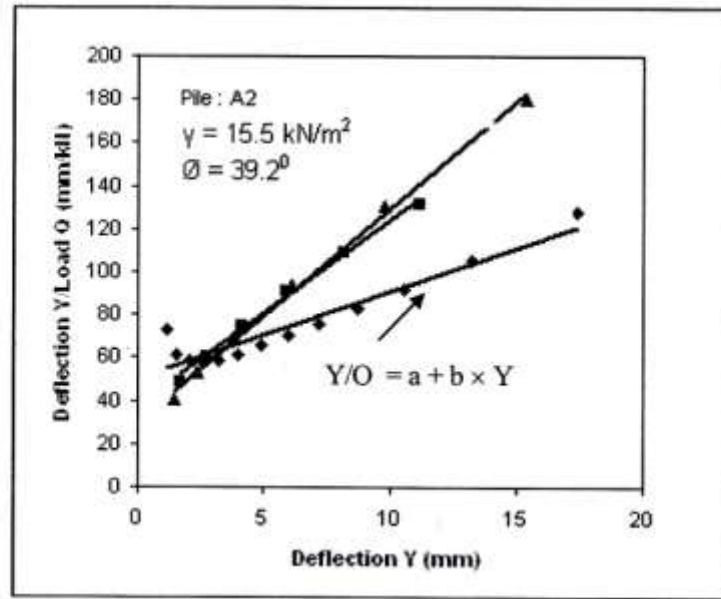
Figure 3 Typical relationship between deflection and deflection/load

The fitting lines are used as an asymptote in Fig.3, then mathematically can be expressed as:

$$Q = Y / (a + b \times Y) \qquad (1)$$
$$Y/Q = a + b \times Y \qquad (2)$$

where, a and b are the parameters of Q ~Y curve.
Equation 2 is divided with Y,

$$1/Q = a/Y + b \qquad (2a)$$

When the deflection Y is infinite (∞) equation 2a becomes as follow:

$$Q = Q_{Y \to \infty} = 1 / b \qquad (3)$$

In which $Q_{Y \to \infty}$ is the assumed ultimate bearing capacity at deflection Y equal to infinite.

The theory of ultimate bearing capacity Q_{ut} of rigid batter piles are computed using the theory suggested by Meyerhof and Ranjan (1973) and Meyerhof (1976), which assumes the rigid batter pile as a vertical rigid pile subjected to an inclined load,

$$\{(Q_{ut} \cos \varepsilon) / Q_a \}^2 + \{(Q_{ut} \sin \varepsilon) / Q_n \}^2 = 1 \qquad (4)$$
$$Q_a = \gamma L N_q A_t + K_s \gamma L \tan \delta A_s/2 \quad \text{(Sand)} \qquad (5)$$
$$Q_a = 9 C_u A_t + \alpha C_u A_s \qquad \text{(Clay)} \qquad (6)$$

where, Q_a is the axial capacity, γ is the unit weight of soil, L is the length of the pile, N_q is the bearing capacity factor, A_t is the area of the pile toe, A_s is the area of the pile shaft, K_s is the average earth pressure coefficient on the shaft and δ is friction angle between sand and pile material, C_u is average undrained shear strength, α is reduction factor.

$$Q_n = 0.125 \gamma B L^2 K_b \qquad \text{(Sand)} \qquad (7)$$
$$Q_n = 0.4 C_u B L K_c \qquad \text{(Clay)} \qquad (8)$$

Q_n is the normal capacity, B is the diameter of pile, K_b is the earth pressure coefficient for pile (Meyerhof et al., 1981). Q_n values for negative batter pile were 1.25 times Q_n values used for positive batter piles. ε is the angle between the axes of the pile and the load. In the case of the

flexible pile of length L, the length L is replaced with ultimate effective length L_{eu} by using the equivalent rigid pile method suggested by Sastry and Meyerhof (1994).

where,

$$L_{eu}/L = 1.65\, K_r^{0.12} \leq 1 \quad \text{(Sand)} \qquad (9)$$
$$L_{eu}/L = 1.5\, K_r^{0.12} \leq 1 \quad \text{(Clay)} \qquad (10)$$
$$K_r = E_p I_p / E_s L^4 \qquad (11)$$

K_r is the relative stiffness of piles (Poulos and Davis, 1980), $E_p I_p$ is flexural rigidity of pile, E_s is horizontal modulus elasticity of soil.

The present ultimate bearing capacity Q_{up} is analyzed as follows:

The theoretical ultimate bearing capacities Q_{ut} divided with the assumed ultimate bearing capacities $Q_{Y\rightarrow\infty}$ values given the factor m. These factors m are corrected with the relative stiffness K_r of the piles for each batter angle β. The fitting lines are used, so that the factor m can be expressed,

$$m = a' + b'\, \text{Log}\,(K_r) \qquad (10)$$

where, a' and b' are the parameters of $m \sim \text{Log}\, K_r$ straight line. The factor m of each batter of pile was shown as follow :

Sand case,

$$m_{\beta-0}^{\circ} = 0.364 + 0.037\, \text{Log}\,(K_r) \qquad (11)$$
$$m_{\beta-15}^{\circ} = 0.489 + 0.042\, \text{Log}\,(K_r) \qquad (12)$$
$$m_{\beta--15}^{\circ} = 0.306 + 0.028\, \text{Log}\,(K_r) \qquad (13)$$
$$m_{\beta-30}^{\circ} = 0.585 + 0.035\, \text{Log}\,(K_r) \qquad (14)$$
$$m_{\beta--30}^{\circ} = 0.456 + 0.050\, \text{Log}\,(K_r) \qquad (15)$$

Clay case ,

$$m_{\beta-0}^{\circ} = 1.138 + 0.278\, \text{Log}\,(K_r) \qquad (16)$$
$$m_{\beta-15}^{\circ} = 0.946 + 0.229\, \text{Log}\,(K_r) \qquad (17)$$
$$m_{\beta--15}^{\circ} = 1.153 + 0.283\, \text{Log}\,(K_r) \qquad (18)$$
$$m_{\beta-30}^{\circ} = 0.740 + 0.149\, \text{Log}\,(K_r) \qquad (19)$$
$$m_{\beta--30}^{\circ} = 0.861 + 0.094\, \text{Log}\,(K_r) \qquad (20)$$

The present ultimate bearing capacity of loading tests results Q_{up} of flexible batter piles in homogeneous sand under horizontal loads can be determined using the factor m as follow:

$$Q_{up}\ \text{single} \qquad = m \times Q_{Y\rightarrow\infty} \qquad (21)$$
$$Q_{up}\ \text{group} \qquad = m \times Q_{Ygroup\rightarrow\infty} \qquad (22)$$

where, Q_{up} single is the present ultimate bearing capacity of piles loading tests results load Q and deflection Y curves.

The present ultimate bearing capacities Q_{up} single and Q_{up} group are found in good agreement compared with the theoretical ultimate bearing capacity Q_{ut} single and Q_{ut} group suggested by Meyerhof and Ranjan (1973) and Meyerhof (1976).

The differences between the theoretical ultimate bearing capacities Q_{ut} and the present ultimate bearing capacities Q_{up} were about 30%.

4. Conclusions

The fitting method can be used for determining the ultimate bearing capacity of rigid and flexible vertical or batter piles in homogeneous sand and clay under horizontal loads also could be apply for group of piles.

The results of model tests on single vertical and batter piles under horizontal loads in homogeneous sand and clay shows that the batter angle (β), the unit weight of soil (γ) and the relative stiffness K_r significantly influences the ultimate bearing capacity of the piles.

The present ultimate bearing capacities Q_{up} are generally in good agreement with the theoretical ultimate bearing capacities Q_{ut} suggested by Meyerhof and Ranjan (1973).

Although the methods of analysis in this study are reasonably supported by the fitting method, it is believed that further testing of model single batter piles and group piles in the field are needed to verify the proposed concepts.

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