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Lateral bearing capacity of rigid piles near clay slopes

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Abstract

Analytical equations were derived to determine the undrained lateral bearing capacity of rigid piles in cohesive soil. Piles in level ground and piles placed at a distance from the crest of a slope were examined, taking account of the effect of the adhesion at the pile–soil interface. The derived analytical solutions were used to develop charts relating the lateral pile capacity to the pile length/diameter ratio, the pile–soil adhesion, the distance of the point of load application from the ground to the pile diameter ratio, the inclination of the slope and the distance of the pile from the crest of the slope to the pile diameter ratio. They were also used to derive a reduction factor which, when multiplied by the lateral bearing capacity for level ground, gives the bearing capacity of the same pile near a slope. In addition, a critical non-dimensional distance between the pile and the crest of the slope, at which the bearing capacity approaches that for a level ground, was determined. The bearing capacity charts obtained for level ground were compared to the classic Broms' charts and to others derived using several different lateral earth pressure distributions along the pile. Comparisons were also made between the results of the proposed method for piles near slopes and those obtained from charts based on upper bound calculations. Finally, the proposed new method was validated through a comparison with the results of a large number of pile load tests, in which a remarkable agreement was observed between the analytical results and the measurements.

Keywords: Piles; Lateral loads; Bearing capacity; Clay; Soil–pile interactions; Slopes

1. Introduction

Short rigid piles or drilled shafts are often used to transfer horizontal loads to the ground from structures such as highway signs, traffic signals, sound barriers, transmission towers, wind turbines, etc., placed near the edge of a slope. In contrast to conventional long flexible piles, the design of these low length/diameter (L/D) piles is primarily governed by the lateral soil failure instead of the yielding of the pile material.

The method most commonly used, at least in the preliminary stage, to determine the ultimate lateral load H_u that can be applied at the head of a short rigid pile in level cohesive soil, is the method by Broms (1964). This method was developed using static analyses and assuming a simplified distribution of the limit soil reaction along the pile length. Results were presented in the form of H_u/c_uD^2 versus L/D graphs, which directly give the ultimate lateral load for piles in clay of undrained shear strength c_u. Similar methods to determine H_u for short piles in a level ground have been proposed by Hansen (1961) and Meyerhof et al. (1981), considering a foundation material having both friction and cohesion and assuming different distributions of soil reaction along the pile.

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Solutions for the lateral bearing capacity of rigid piles in level cohesive soil can also be obtained using pile statics and the ultimate lateral soil reaction per unit length (p_u) distributions with depth adopted in the various *p–y* curve equations commonly used in lateral pile analyses. In such analyses, the ultimate lateral soil reaction per unit pile length is determined as

$$p_u = N_p c_u D \tag{1}$$

where N_p is a bearing capacity factor which varies with the depth to diameter ratio (z/D).

Several N_p versus z/D relationships obtained experimentally, analytically or numerically (Stevens and Audibert, 1980; Murff and Hamilton, 1993; Matlock, 1970; Reese and Welch, 1975; Bhushan et al., 1979; Reese et al., 1975; Broms, 1964; Hansen, 1961; Jeanjean, 2009; Georgiadis and Georgiadis, 2010) are presented in Fig. 1, demonstrating a remarkable scatter. As pointed out by Georgiadis and Georgiadis (2010), among the various causes contributing to this scatter, the dependence of p_u on the pile–soil adhesion is very significant. Based on the results of 3D finite element analyses and comparisons to pile load test results, they proposed the following N_p versus z/D relationship which takes into account the pile–soil adhesion:

$$N_p = N_{pu} - \left(N_{pu} - N_{po}\right) e^{-\lambda(z/D)} \tag{2}$$

where λ is a non-dimensional factor equal to $\lambda = 0.55 - 0.15\alpha$, α is the adhesion factor which is defined as the adhesion to undrained shear strength ratio and ranges from 0 (smooth pile) to 1 (rough pile), N_{po} is the bearing capacity factor at the ground surface equal to $N_{po} = 2 + 1.5\alpha$ and N_{pu} is the ultimate lateral bearing capacity factor for deep failure, derived using the following lower bound plasticity analytical relationship by Randolph and Houlsby (1984):

$$N_{pu} = \pi + 2\Delta + 2\cos\Delta + 4\left(\cos\frac{\Delta}{2} + \sin\frac{\Delta}{2}\right) \tag{3}$$

where $\Delta = \sin^{-1}\alpha$.

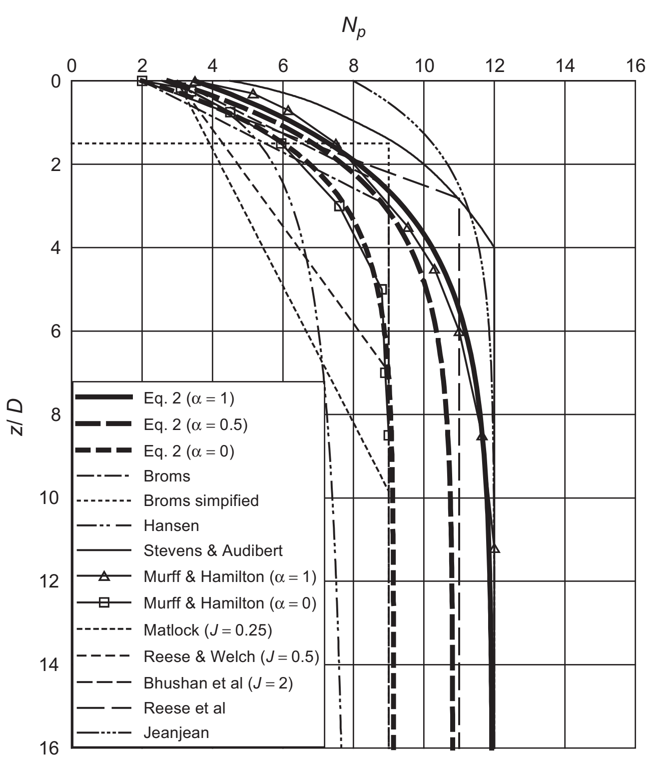

Fig. 1. Variation in lateral bearing capacity factor with depth for level ground.

Information concerning the behaviour of rigid piles near the crest of a slope is rather limited. The results of experimental and numerical analyses of rigid piles, placed at locations of various distances from the crest of a sand slope (Chae et al., 2004), have shown that the lateral bearing capacity is reduced even at distances greater than four pile diameters from the crest. Similarly, the results of centrifuge pile tests in sand, presented by Mezazigh and Levacher (1998), have shown that the pile behaviour is affected by the slope even at a distance of eight pile diameters from the crest. The lateral bearing capacity of a rigid pile near the crest of a clay slope has been investigated by Stewart (1999). Based on an upper bound plasticity analysis, which assumed weightless soil and zero adhesion at the pile–soil interface, he provided graphs of the reduction factors on H_u versus the distance from the crest for free-head piles. According to these graphs, the effect of the slope diminishes at a distance not exceeding four pile diameters.

To study the effect of the distance between the pile and the crest of a clay slope, on the lateral pile behaviour, Georgiadis and Georgiadis (2012) performed a detailed 3D finite element study which led to the modification of Eq. (2). The resulting variation in N_p with z/D is shown in Fig. 2. As seen in this figure, bearing capacity factor N_p is equal to the bearing capacity factor for horizontal ground, given by Eq. (2), up to critical depth z_c. Below this critical depth, N_p is determined from the following equation:

$$N_p = N_{pu} - \left(N_{pu} - N_{pc}\right) e^{-\lambda\alpha_\theta(z - z_c)/D} \tag{4}$$

where α_θ is a factor depending on the inclination of the slope (θ).

$$\alpha_\theta = 1 - \frac{\sin\theta(1 + \sin\theta)}{2} \tag{5}$$

where z_c is the critical depth which depends on the distance between the pile and the crest of the slope (b).

$$z_c/D = 8.5 - 10\log_{10}\left(8 - b/D\right) \tag{6}$$

N_{pc} is the bearing capacity factor at the critical depth, obtained from Eq. (2) for $z = z_c$. Typical diagrams obtained through the above equations are presented in Fig. 3, demonstrating the effect of θ and b/D on the N_p versus z/D relationship. It is noted that finite element analyses have shown that unless the slope is close to failure, with a safety factor well below those used in the slope design, the pile lateral earth pressure can be accurately approximated by the above equations.