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Undrained limiting lateral soil pressure on a row of piles

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ABSTRACT

The displacement finite element, lower and upper bound finite element limit analysis and analytical upper bound plasticity methods are employed to investigate the undrained limiting lateral resistance of piles in a pile row. Numerical analyses and analytical calculations are presented for various pile spacings and pile–soil adhesion factors. The numerical results are shown to be in excellent agreement with each other and also with the theoretical upper bounds produced by the analytical upper bound calculations. Based on the numerical and analytical results, an empirical equation is proposed for the calculation of the ultimate undrained lateral bearing capacity factor. This equation is subsequently used to calculate *p*-multipliers applicable to the lower part of piles in pile rows, which are compared to multipliers available in the literature (that are constant with depth). The comparison shows significant differences, indicating that the amount of reduction in lateral resistance due to group effects is not constant with depth as routinely assumed in practice.

1. Introduction

The lateral behaviour of piles in pile groups is commonly analysed with the well-known "*p*–*y*" method in which pile group effects are taken account of through the application of a reduction factor, called the *p*-multiplier, on the assumed distribution of the ultimate lateral load per unit length p that can develop along the length of a single pile.

Significant research effort has focused on the determination of the limiting lateral load (p_u) distribution with depth for single piles in clay (e.g. Matlock [1], Reese and Welch [2], Stevens and Audibert [3], Murff and Hamilton [4], Jeanjean [5], Georgiadis and Georgiadis [6,7]), which is crucial for the estimation of the load – deflection (p–y) response along the pile length. It is well established that p_u increases with depth in the upper part of the pile (where wedge-type failure is observed) up to a maximum value and remains constant in the lower part of the pile (where failure is conceptualised to take place with a flow-around mechanism). Randolph and Houlsby [8] developed lower and upper bound plasticity solutions for the calculation of the maximum load per unit length, and proposed the following lower bound equation, expressed in terms of the single-pile lateral bearing capacity factor N_{p1}:

$$N_{p1} = \frac{p_u}{s_u D} = \pi + 2\arcsin\alpha + 2\cos(\arcsin\alpha) + 4\left[\cos\left(\frac{\arcsin\alpha}{2}\right) + \sin\left(\frac{\arcsin\alpha}{2}\right)\right] \quad (1)$$

where s_u is the undrained shear strength, D is the pile diameter and α is the pile soil adhesion factor (=limiting interface shear stress/undrained shear strength). Martin and Randolph [9] showed that the above expression gives the theoretically exact solution for all practical purposes (up to 0.8% difference from an upper bound solution).

In order to take account of group effects, several *p*-multipliers have been proposed for piles in clay, which have been based primarily on full-scale lateral load tests (e.g. Meimon et al. [10], Brown et al. [11], Rollins et al. [12], Rollins et al. [13], Lemnitzer et al. [14]) and to a lesser extent on 1 g model tests (e.g. Chandrasekaran et al. [15]) and centrifuge model tests (e.g. Cox et al. [16], Illyas et al. [17]). These *p*-multipliers have been back-calculated from measured pile head load-displacement relationships, not taking account of the expected variation of group effects with depth, and therefore a single value is assigned to each pile. Furthermore, it is common practice to assume a single average value for all piles in the same pile row, which is also often assumed to be independent of pile spacing within the row.

Unlike the problem of single piles in clay for which, as shown above, the ultimate limiting pressure can be accurately calculated, very limited studies have been made for piles in pile groups. These include two-dimensional numerical studies for both active and passive loading of pile groups, reported by Chen and Poulos [18,19], Bransby [20], Bransby and Springman [21] and Chen and Martin [22].

This paper presents two-dimensional displacement finite element analyses, lower and upper bound finite element limit analyses and analytical upper bound solutions for the determination of the limiting lateral soil pressures and the associated *p*-multipliers

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Nomenclature

D	pile diameter	v_o	pile lateral velocity
E_p	modulus of elasticity of pile	v, Δv	internal lateral velocities of failure mechanism
E_u	undrained modulus of elasticity	y	lateral pile displacement
f_m	p-multiplier	α	adhesion factor
L_i	length of velocity discontinuity i	δ, λ, β_1, β_2	geometrical optimisation parameters
N_p	lateral bearing capacity factor	$\dot{\gamma}$	shear strain rate
N_{p1}	single pile lateral bearing capacity factor	ΔW_p	work done by internal stresses
p_u	ultimate lateral load per unit length	v_p	Poisson's ratio of pile
R	pile radius	v_u	undrained Poisson's ratio
s	centre-to-centre pile spacing	τ_f	ultimate shear stress along discontinuity
s_u	undrained shear strength		
s_1	pile spacing beyond which $N_p = N_{p1}$		

for piles in infinitely long rows. The problem definition is illustrated in Fig. 1.

2. Numerical analyses

2.1. Displacement finite element analyses

Displacement finite element analyses were performed with the finite element program Plaxis 2D Version 2011.02 (Brinkgreve et al. [23]), in which a row of infinitely long cylindrical piles were displaced laterally in an infinite elastic-perfectly plastic soil medium, as shown in Fig. 1. Analyses were performed with several different centre-to-centre pile spacings s and the same pile diameter D = 1 m.

A typical finite element mesh for s/D = 3 is shown in Fig. 2a and a detail of the mesh refinement in Fig. 2b. As seen in these figures, due to the symmetry of the geometry and the loading conditions, only a single pile was modelled, with zero normal displacement boundaries (symmetry planes) positioned at a distance of $s/2$ from the pile centre on either side of the pile. The other two boundaries were also fixed in the normal direction and were positioned at 15D from the pile centre. The meshes used in the analyses consisted of approximately 6000 15-noded triangular elements for both the piles and the surrounding soil, with interface elements placed between the piles and the soil.

The soil was modelled as a linear elastic – perfectly plastic Tresca material with undrained shear strength s_u = 100 kPa, undrained Young's modulus $E_u = 200{\cdot}s_u$ and undrained Poisson's ratio v_u = 0.495. The piles were modelled as linear elastic with the elastic properties of reinforced concrete: Young's modulus $E_p = 2.9 \times 10^7$ kPa and Poisson's ratio v_p = 0.1. Various limiting shear stresses τ_f (adhesion) were assigned to the pile–soil interfaces in order to investigate the influence of the pile–soil adhesion factor α (=τ_f/s_u), while high elastic normal and shear stiffnesses were selected in order to approximate rigid-plastic interface behaviour.

The analyses were performed by applying prescribed displacement at all nodes of the pile diameter. The undrained bearing capacity factor N_p for each case was subsequently calculated dividing the resulting ultimate reaction force by s_uD. It is noted that collapse was well defined in all cases, since an ultimate load which remained constant with increasing pile displacement was always observed.

2.2. Finite element limit analyses

Upper and lower bound finite element limit analyses were performed using the formulations originally developed by Sloan ([24,25]) and further improved by Lyamin and Sloan ([26,27]) and Krabbenhoft et al. ([28,29]). Fig. 3 shows a typical upper bound finite element mesh after completion of the adaptive remeshing process (at failure) for s/D = 3 and α = 0.5. Analyses were performed with various normalised pile spacings s/D and pile–soil adhesion factors α. Four adaptive iterations were usually employed for mesh refinement with the number of elements gradually increasing from

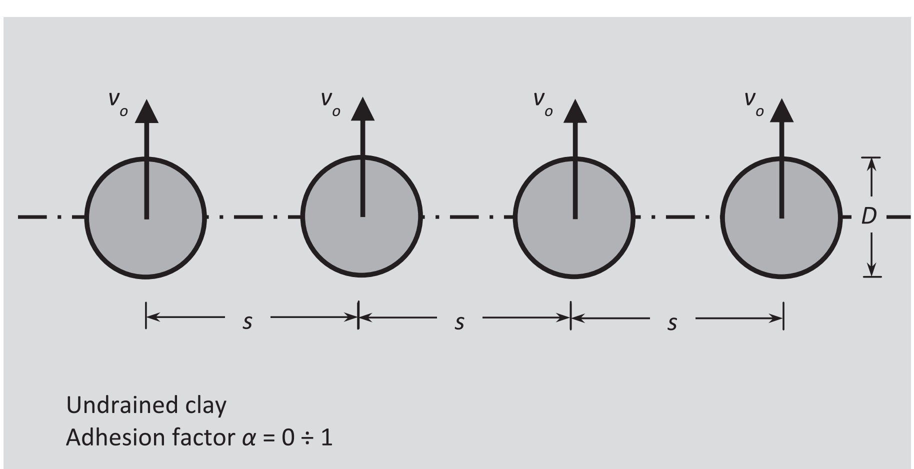

Fig. 1. Problem definition.