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Ultimate lateral bearing capacity of tetrapod jacket foundation in clay

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ABSTRACT

The tetrapod jacket foundations that are always used to support offshore wind turbines have been investigated primarily in laboratory experiments. In this study, the ultimate lateral soil resistance on this type of foundation was investigated using the finite element method and the analytical upper bound plasticity method. The numerical results show good agreement with the theoretical upper bound solutions under the same pile spacings (S) and soil-pile adhesion factors (α). Three distinct failure mechanisms (mechanisms A, B and C) were established in terms of different pile spacings. The ultimate lateral pressure was subsequently determined using numerical analyses with consideration of the loading direction. The most critical loading direction angles (θ) vary with the soil-pile adhesion factors, and are $\theta = 0$ for $\alpha = 1$ and $\theta = \pi/4$ for $\alpha = 0$. Selected empirical equations were proposed to predict the ultimate lateral bearing capacity for engineering practice, considering the pile spacing, soil-pile adhesion and loading direction.

1. Introduction

The lateral bearing capacity of the pile foundation is the key design point for pile-supported wind turbines subjected to loads from wind, waves and currents. Due to the high cost of fully instrumented lateral pile load tests and centrifuge model tests, analytical methods present attractive alternatives. Many researchers investigated the ultimate horizontal bearing capacity of a single pile using the limit analysis method. Murff & Hamilton [1] found that the ultimate lateral resistance of a monopile increased with depth, up to a maximum value, and this resistance was associated with a plane strain flow-around mechanism. The upper and lower bound solutions for a two-dimensional lateral circular pile were first obtained by Randolph & Houlsby [2], and these solutions were exact for fully rough piles because the lower and upper bounds were the same. However, the collapse load obtained from upper bound solution does not agree with the result from lower bound solution for low pile-soil adhesion ($\alpha < 1$). The problem was first detected by Murff et al. [3]. Therefore, Christensen & Niewald [4] and Martin & Randolph [5] improved the upper bound solutions by optimizing new mechanisms, and the combined upper-bound mechanism presented by Martin & Randolph [5] provided the best solution so far. In recent years, a series of research studies that consider pile group effects has been performed by Georgiadis et al. [6–8]. Specifically, the lateral soil resistance (for the case of two laterally loaded, side-by-side piles in clay) was calculated using the analytical upper bound method and numerical analysis [6]. Subsequently, two other studies [7,8] were conducted that considered the effect of loading direction and the case of a row of piles.

Because the turbine capacity and water depth of wind farms are both increasing, the jacket foundation is increasingly applied, especially the tetrapod jacket foundation. Mostafa et al. [9] established a dynamic analysis model of the jacket foundation in the North Sea using a finite element package (ASAS) and investigated the effect of group piles and dynamic soil resistance on the lateral bearing capacity of the foundation. In a recent work by Abhinav and Saha [10], the NREL 5 MW offshore wind turbine supported by the tetrapod jacket foundation under random wave loading was designed and analyzed for western offshore sites in India. The response of the jacket-supported wind turbine under the soil-structure interaction (SSI) was compared with the response without the SSI. Moreover, Mao et al. [11] established a 1/10 scale experimental model to study the influence of foundation degradation on the offshore tetrapod jacket platform. Although many researchers have investigated the tetrapod jacket foundation based on engineering projects and experiments, rather limited work has been published using theoretical methods.

The objective of this study is to obtain the theoretical results for the ultimate lateral soil pressure on the tetrapod jacket foundation

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using the analytical upper bound plasticity method and the finite element method. Finite element analysis is subsequently applied to investigate the effect of loading direction. Finally, selected empirical equations are proposed based on the numerical study.

2. Numerical finite element analyses

All numerical finite element analyses were performed using the software package Plaxis 2D Version 8 (Brinkgreve et al. [12]), in which the tetrapod jacket foundation, assumed as four infinitely long cylindrical piles (Fig. 1), was presented in an infinite elastic-perfectly plastic soil medium. Various adhesion strengths and pile spacings (S) were considered, and the pile diameter was taken as D = 1 m in all analyses. The case in which the loading direction is parallel to the pile-to-pile axis was first discussed. Due to the symmetry of both the geometry and loadings, only two piles in a column were considered. The left mesh boundary is the symmetrical face, and the normal displacements on this boundary were zero. The other three boundaries were all fixed both in the normal and shear directions. Furthermore, the boundaries were positioned at a distance of 10D from the pile group centre to avoid boundary effects. "Very fine" mesh densities were used in all analyses. The model consisted of approximately 2300 15-noded triangular elements for both the piles and the soil. A typical finite element mesh for normalized pile spacing S/D = 2.5 is shown in Fig. 2.

Additionally, the piles and soil were modelled as a linear elastic material and an elastic/perfectly plastic Tresca material, respectively. The soil properties include the following values: undrained strength s_u = 100 kPa, undrained Young's modulus $E_u = 2 \times 10^4$ kPa, and Poisson's ratio υ_u = 0.495. The piles were modelled using the elastic properties of concrete, resulting in a Young's modulus $E_p = 2.9 \times 10^7$ kPa, and a Poisson's ratio υ_p = 0.1. Because the pile surface might be smooth or notably rough, during the design, the shear strength of the soil-pile interface was expressed as α times the strength of the adjacent soil ($\alpha = \tau_f/s_u$, where τ_f is the limiting pile-soil adhesion). Because the soil was modelled using the Tresca material, the shear strength was independent of the normal stress. Therefore, the initial stresses (which were adopted in all analyses) were zero. Moreover, the analyses were performed by applying the prescribed displacement to all nodes in the pile diameter. Different pile spacings were modelled by adjusting the left mesh boundary and the relative positions of the piles.

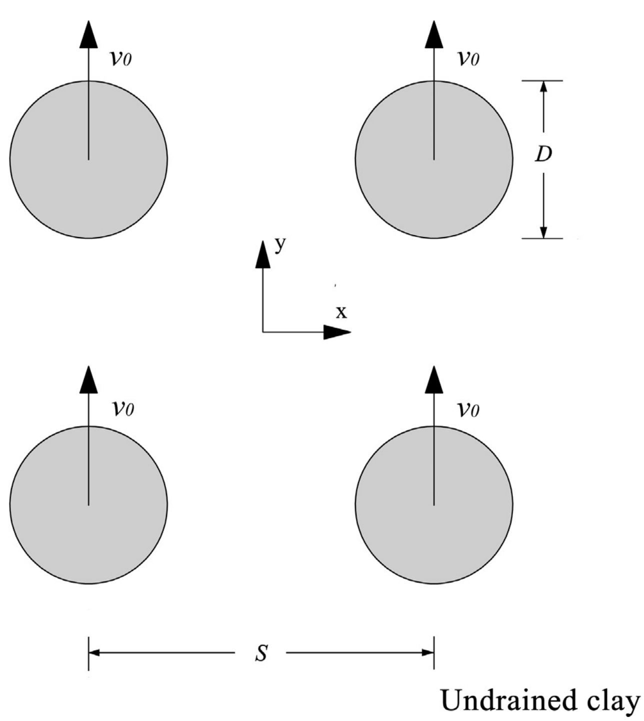

Fig. 1. Problem definition: Tetrapod jacket foundation displaced at the pile-to-pile axis.

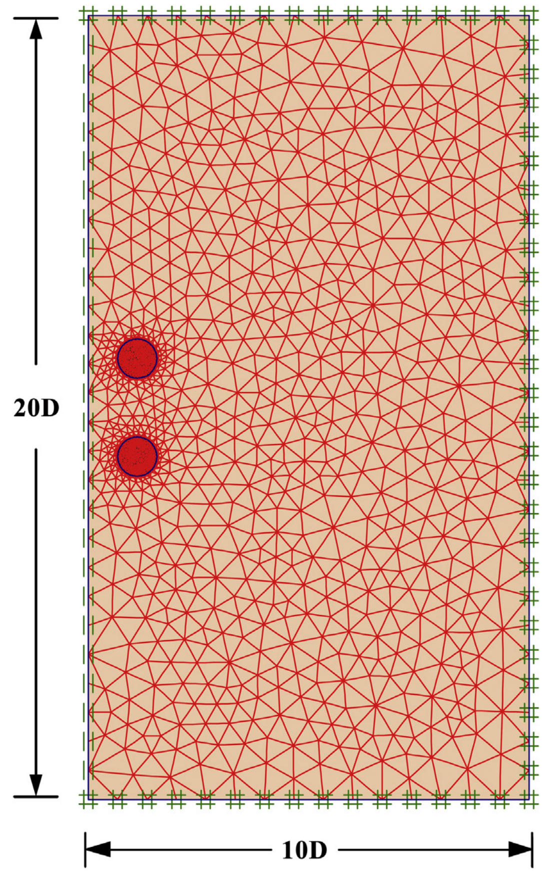

Fig. 2. Finite-element mesh with boundaries.

The variation in the bearing capacity factor N_p ($N_p = P_u/s_u\ D$, where P_u is the ultimate load per unit length) with the normalized pile spacings S/D for various soil-pile adhesions was easily obtained from the displacement finite element analyses. The typical curve for the case of an entirely rough pile (α = 1) is shown in Fig. 3, in which the bearing capacity factor N_p reaches the single-pile value of 11.94 [2]. This value is considered to be maximum at a relatively large pile spacing ($S/D > 5.2$). The bearing capacity factor generally decreases with decreasing pile spacing. The curve in this phase consists of three lines. The gradients of the lines increase from larger to smaller pile spacings. The variation of N_p with S/D can be explained by considering the change in the failure mechanisms for different pile spacings. Four different failure mechanisms are illustrated in Fig. 4 for four normalized pile spacings S/D = 1.4, 2.5, 4, and 6. As shown in Fig. 4a, in the low pile spacing range ($S < 1.65D$), the inner soil surrounded by the four piles moves as a rigid body at the same velocity together with the piles, and the plastic deformation zones only exist at the outer region of the mechanism. For intermediate pile spacings of S_1 (1.65D) and S_2 (3.75D), the failure mechanism can be observed in Fig. 4b. Specifically, the inner soil moves (unlike the case in Fig. 4a) in the direction opposite to the piles, and undergoes plastic deformation. When the pile spacing increases beyond S_2, the outer portion of the mechanism changes significantly with two