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Research Paper

Behaviour of flexible piles subjected to inclined loads

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ABSTRACT

The behaviour of the piles under inclined loads is a topic not fully investigated in the literature. No experimental results from full-scale pile tests are available so that numerical analysis can be an interesting tool to provide useful results about the pile behaviour under this loading condition. In this study, a three-dimensional finite element approach is used to analyse the response of reinforced concrete flexible piles to inclined loads. Appropriate constitutive models are adopted to account for the nonlinear behaviour of the pile and the soil. In particular, the occurrence of plastic strains in the soil, concrete cracking and steel yielding in the pile as well as the occurrence of slip and gap at the pile–soil interface are adequately modelled. To assess the reliability of the method, some loading tests documented in the literature concerning axially or laterally loaded piles are first simulated. A fairly good agreement is found between numerical and experimental results. The geotechnical model and the pile from the above-mentioned tests are considered to highlight some characteristic aspects of the response of flexible piles to inclined loads. In particular, the analysis results show that a flexible pile can experience a flexural or an axial behaviour depending on the load inclination. Load inclination also influences significantly both the stiffness and the bearing capacity of the soil–pile system. Comparisons with the results from some empirical solutions proposed in the literature to evaluate the bearing capacity of the piles under inclined loads are also shown.

1. Introduction

Pile foundations of engineering works such as bridges, retaining walls or offshore structures are frequently subjected to the combined action of horizontal and vertical loads. Considering the difficulty in accounting for the effects of the simultaneous presence of these loads for a prediction of the pile response, in the current applications the case of the pile under vertical load is often analysed separately from that of the pile subjected to horizontal load. An additional reason for using this uncoupled approach is that the resulting value of the pile bearing capacity generally is on the safety side. Specifically, the ultimate load of a horizontally loaded pile should increase when a vertical load is also applied at the pile head. Similarly, the presence of a horizontal load should improve the axial bearing capacity of the pile [1]. However, in the light of the modern design regulations, the simultaneous presence of vertical and horizontal loads (i.e., of inclined loads) applied at the pile head should be considered for a more rational design of the pile foundations [2].

The behaviour of the rigid piles embedded in homogeneous as well as layered soils and subjected to inclined loads was extensively studied by Meyerhof and his co-workers on the basis of the experimental results from a great number of loading tests performed on small-scale piles. These studies have laid firmly the concepts for the design of the rigid piles [1–8]. In particular, the ultimate load Q_u at an inclination angle α (measured from the horizontal direction) can be evaluated using the following equation [3]:

$$\left[\frac{V}{Q_a}\right]^2 + \left[\frac{H}{Q_h}\right]^2 = 1 \tag{1}$$

where V and H denote the vertical and horizontal components of Q_u (i.e., $V = Q_u \sin\alpha$ and $H = Q_u \cos\alpha$), Q_a and Q_h are the ultimate loads under pure vertical and horizontal loading respectively. More recently, Cho and Kulhawy [9] proposed the alternative equations (with α expressed in degree):

$$V = Q_L\left(\frac{90-\alpha}{90}+1\right) + Q_P\left(\frac{90-\alpha}{90}+1\right)^{7.3} \tag{2a}$$

$$H = Q_h\sqrt{\cos\alpha} \tag{2b}$$

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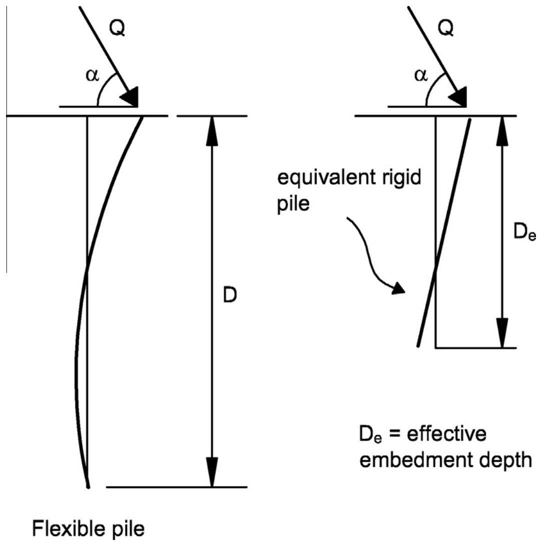

Fig. 1. Deformation pattern of a flexible pile and the equivalent rigid pile.

where Q_L is the shaft capacity and Q_P is the base capacity of the axially loaded pile. The values of Q_a, Q_h, Q_L and Q_P in the above equations can be evaluated using some conventional methods available in the literature [10,11].

However, most field piles behave as flexible structures which bend under the action of inclined loads. In these circumstances, the assumption of rigid pile cannot be in principle accepted. Meyerhof et al. [7] suggested to analyse the behaviour of a flexible pile using the model of the equivalent rigid pile which is characterised by an "effective embedment depth" [12,13]. The concept of effective embedment depth is schematically shown in Fig. 1. However, as it can be seen from this figure, the behaviour of the equivalent rigid pile is rather different from that of the flexible pile. The equivalent pile rigidly rotates with the rotation centre located at a certain depth from the pile top, whereas the flexible pile bends with the maximum deflection confined in the upper portion of the pile. Moreover, the structural properties of the pile, which are partly considered in the equivalent rigid pile model, should be adequately taken into account for a realistic prediction of the pile behaviour. Therefore, using the solutions for rigid pile should in principle lead to an approximate evaluation of the response of flexible piles to inclined loads.

A more comprehensive approach is presented in this paper, in which a numerical solution based on the finite element method is used to perform a three-dimensional (3D) analysis of the behaviour of reinforced concrete (r.c.) piles subjected to inclined loads. In this approach, the nonlinear behaviour of the soil and pile is accounted for using suitable constitutive models which allow the occurrence of plastic strains in the soil, concrete cracking and reinforcement yielding in the pile to be reliably simulated. In addition, slip and gap can occur at the soil–pile interface. After predicting successfully the response experienced by some piles during horizontal and vertical loading tests documented in the literature, the proposed approach is applied to investigate the influence of the load inclination on the behaviour of flexible piles.

2. Constitutive models

The choice of a constitutive model to analyse the behaviour of structures interacting with the soil, is often conditioned by the material parameters that are available for the case study under consideration. When routine parameters are only available or there is a lack of specific experimental data, the use of sophisticated models is not completely justified to predict the mechanical behaviour of the materials involved. Considering that in the current applications this is often the case, the constitutive models employed in the present study are relatively simple and require few material parameters as input data. In addition, these parameters can be in principle obtained from conventional geotechnical and structural tests.

Specifically, an elastic perfectly plastic model with Mohr–Coulomb failure criterion and flow rule of non-associated type is considered for modelling the soil behaviour. The Mohr–Coulomb criterion is replaced by the Tresca criterion under undrained conditions. Therefore, the soil parameters required by this constitutive model for performing an analysis under drained conditions are the shear modulus G (or the Young modulus E') Poisson's ratio ν', shearing resistance angle φ', effective cohesion c' and angle of dilatancy ψ. The shear modulus G, Poisson's ratio ν_u and the undrained shear strength S_u are on the contrary required for an analysis under undrained conditions.

The constitutive model for the concrete is based on the plasticity theory for compressive stresses and the fracture mechanics for tensile stresses [14–17]. This model is suitable for structures that are subjected to monotonic loading. For compressive stresses, the concrete behaves as an elastic plastic material with isotropic hardening/softening and associated flow rule. For tensile stresses, a different model is used to simulate the occurrence and development of cracking. Specifically, cracking occurs when the stress state reaches a "crack detection" surface which is described by a relationship of Mohr–Coulomb type [17]. This surface also allows the orientation of the crack to be defined. It is assumed in fact that, at a given stress state, the crack direction is normal to the above-mentioned surface. Once the occurrence and orientation of crack are detected, the damaged elasticity theory is used to describe the post-failure behaviour of the concrete with open cracks [15]. Specifically, it is assumed that the material loses strength through a softening mechanism which is dominantly a damage effect with the open cracks that provoke a reduction of the concrete stiffness. The cracks close again when the stress across them turns out to be compressive. No permanent strain associated with cracking occurs. In addition, it is assumed that the cracks are smeared on the concrete zones affected by this process.

A stress–strain relationship under uniaxial conditions has to be defined to use the described constitutive model. The relationship assumed in the present study is shown in Fig. 2. For the sake of

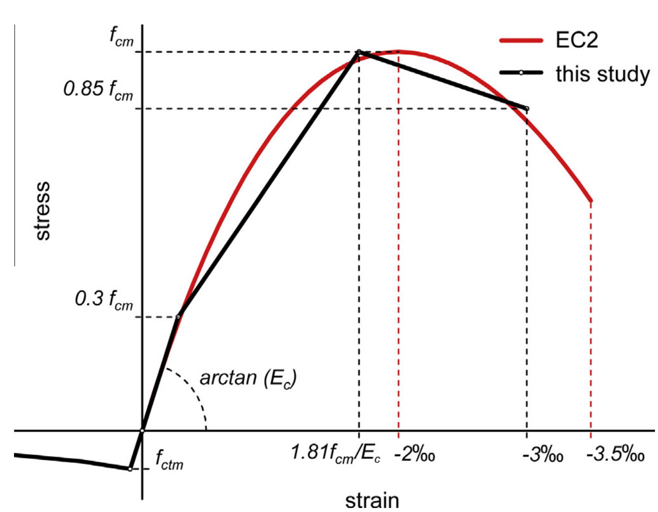

Fig. 2. The stress–strain relationship assumed for the concrete and that recommended by the EC2 design regulation [16].