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On the pile response to inclined loads

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Abstract

In this paper, a three-dimensional finite element approach is used to analyse the response of reinforced concrete piles to inclined loads. Appropriate constitutive models are considered 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 are reliably simulated. Some characteristic aspects of the behaviour of piles under inclined loads are highlighted.

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Keywords: pile foundation; inclined loads; three-dimensional finite element analysis; reinforced concrete

1. Introduction

Pile foundations of bridges, retaining walls and offshore structures are generally subjected to the combined action of horizontal and vertical loads. Considering the lack of reliable practical methods, in the current applications the case of the pile under vertical load is often analysed separately from the case of the pile subjected to horizontal load. For a rational design of the piles, however, the presence of inclined loads should be taken into account in the calculations [1]. The behaviour of the rigid piles embedded in homogeneous or 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 conducted on small-scale piles [2-8]. Nevertheless, the piles generally 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. suggested analysing the behaviour of a flexible pile using the model of the equivalent rigid

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pile characterized by an "effective embedment depth" [9,10]. However, the behaviour of the equivalent rigid pile is rather different from that of a flexible pile. The equivalent pile rigidly rotates around a pivot point 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 in part considered in the equivalent rigid pile model, should be adequately taken into account for a realistic prediction of the pile behaviour, especially for high levels of loading. A more comprehensive approach based on the finite element method is used in this paper to analyse the behaviour of reinforced concrete (r.c.) piles subjected to inclined loads under three-dimensional (3D) conditions. 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. Using the present approach, the influence of the load inclination on the behaviour of r.c. piles is analysed.

2. Method of analysis

The finite element code ABAQUS [11] is used in the present paper to analyse the response of a r.c. pile to inclined loads. This code allows several constitutive models to be used for the soil, concrete and steel. Considering that in the current applications only routine parameters are often available, 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 obtained from conventional tests. Specifically, an elastic-perfectly plastic Mohr–Coulomb model with flow rule of non-associated type is considered for modelling the soil behaviour. The soil parameters required by this constitutive model are the elastic parameters (Young's modulus E' and Poisson's ratio ν') and the strength parameters (shear resistance angle φ', effective cohesion c' and angle of dilatancy ψ). Regarding the concrete, it is assumed that, for compressive stresses, this material 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 with the crack direction being normal to this surface. After this condition, the material is subjected to a softening mechanism which is dominantly a damage process 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 [11,12]. A stress-strain relationship under uniaxial conditions like that shown in Figure 1, is required by this model.

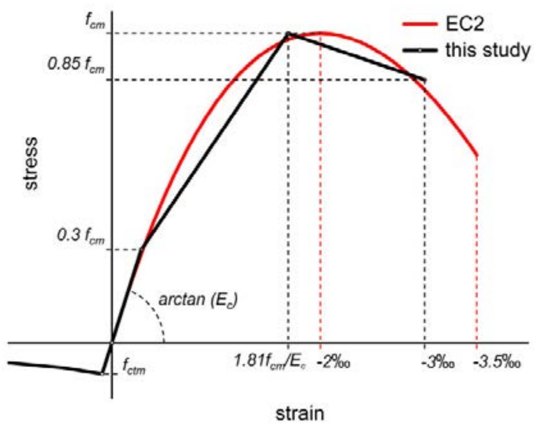

Fig. 1. Stress-strain relationship assumed for the concrete and that recommended by the EC2 design regulation [13].