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Ultimate bearing capacity of laterally loaded piles in clay – Some practical considerations

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ABSTRACT

The paper re-visits the topic of ultimate bearing capacity of laterally loaded piles in clay. The paper first presents a review of various recommendations made by design guidelines and industry practitioners which illustrates inconsistency and need for further work. A literature study is therefore performed and a generalised recommendation of the ultimate lateral capacity of piles in clay that is self-consistent and flexible for a wide range of conditions is made. The paper further investigates two practical considerations often encountered in design, namely the effect of axial loading and the effect of soil strength anisotropy by means of finite element analyses. Practical methods to account for these effects are proposed.

1. Introduction

Piles, particularly offshore piles, often have to be designed to resist lateral loading. Load transfer curves (commonly known as p-y springs) which express the lateral soil resistance versus deflection are usually used in design and the overall pile response is solved by a beam-column analysis. This paper deals with the ultimate lateral bearing capacity for piles in clay, i.e., the peak value for the p-y springs. It is well established that for a laterally loaded slender pile in clay, two soil failure mechanisms can be involved, as illustrated in Fig. 1. In the upper part, soil fails in a conical wedge mechanism that extends to the soil surface. If suction is not available (i.e. allow separation), only a passive wedge is mobilised on the front side (Fig. 1a), with a gap potentially opening up on the rear side. Whereas if suction is available, an active wedge is also mobilised on the rear side of the loading direction. At a certain depth, soil fails in a localised flow around mechanism (Fig. 1b), as the soil resistance encountered in this mechanism becomes smaller (i.e. preferential) than the wedge mechanism.

There have been extensive studies in the literature on the limiting lateral bearing capacity of pile foundations in clay. To name only a few, these include, for example, experimental studies: [8,14,19,22]; analytical: [13,15,18,20,21]; and numerical: [4,5,16,20,21]. However, in the industry, a common agreement seems not reached on what is the limiting pile capacity in clay and its evolution with depth. Different recommendations are seen in various sources. Design engineers therefore may face the question on which recommendation to follow.

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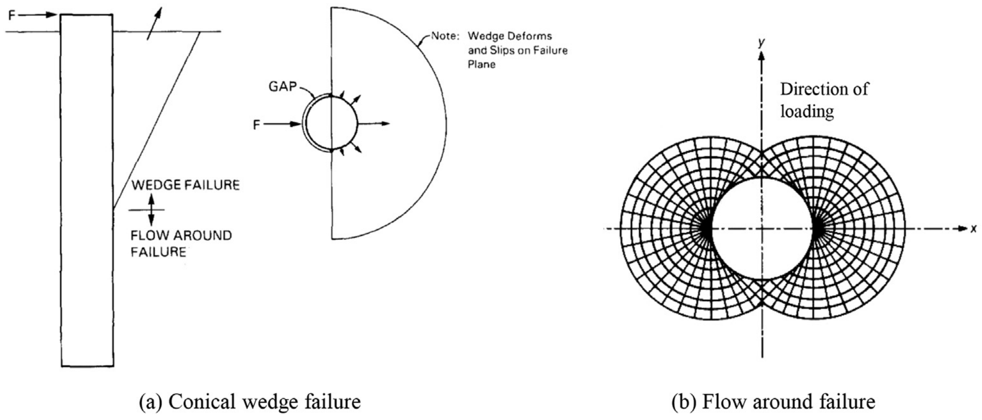

Fig. 1. Illustration of (a) conical wedge failure mechanism (after Murff and Hamilton [15], and (b) flow around mechanism (after Randolph and Houlsby [18].

A pile loaded laterally can often be subjected to axial loading at the same time. A further question often faced by design engineers is how to account for the effect of axial loading on the lateral pile capacity. In the current industry practice, the interaction between axial and lateral loading are usually not explicitly considered. Instead, piles are designed with separate verifications for axial and lateral loading.

It is noted that most analytical and numerical studies in the literature have almost exclusively considered isotropic material behaviour, with a single measure of the undrained shear strength s_u, based on which solutions are developed. However, it is well known that clay exhibits different undrained shear strengths, depending on the shearing mode/direction with respect to deposition plane and major principal stress direction. Different testing methods normally measure different undrained shear strengths. In the current offshore industry practice, anisotropically consolidated undrained triaxial compression (CAUC), anisotropically consolidated triaxial extension (CAUE) and direct simple shear (DSS) strengths are typically measured in the laboratory. Unconsolidated and undrained compression (UU) tests are also often performed offshore and onshore, which measure soil strengths that are known as s_u^{UU}. In addition, soil resistance of in situ CPT or T-bar tests are often correlated to undrained shear strength by applying empirical/theoretical correlations. The question faced by design engineers is how to account for shear strength anisotropy, or in other words, what shear strength should be used to compute the ultimate lateral bearing capacity while using the solutions derived for isotropic material?

This paper re-visits the topic of the ultimate lateral bearing capacity of pile foundations in clay in an attempt to tackle the three important questions faced by design engineers, namely: 1) what is the limiting lateral bearing pressure in clay and its evolution with depth in ideally isotropic material; 2) what is the effect of axial loading on lateral capacity; 3) what is the effect of strength anisotropy? Practical guidance is provided on these topics.

2. Methodology

In this study, a combined methodology of literature study and finite element analyses (FEA) is adopted. For the first question, literature study is the main method, complemented by FEA results. For the second and third questions (effect of axial loading and strength anisotropy), FEA is mainly relied on. This section provides a brief description of the finite element model.

2.1. Finite element model

The FEA are performed with commercial finite element program Plaxis 3D [17]. The finite element model is shown in Fig. 2. The pile is 2.14 m in diameter (D), and 40 m embedded in soil. Due to symmetry condition, only half of the pile is modelled. The pile is modelled as a linearly elastic solid object, assigned with bending stiffness equivalent to a steel hollow pile 60 mm in wall thickness. For ease of extraction results from analyses, a beam with a small bending stiffness, 1/1000 relative to the actual pile, is attached to the pile at the pile centre, as illustrated in Fig. 2. The dummy beam is enforced to deform together with the pile. The cross-section forces (shear force and bending moment) of the pile are simply 1000 times of those of the beam, which are direct outputs from the finite element program.

The finite element model is discretised with 10-node tetrahedral elements with biased mesh densities. A refined zone with a radius of three pile diameters from the centre line of the pile is used, in which typical element dimension is about 0.3D. Outside the refined zone, the element size increases gradually with distance from the pile. The finite element mesh is calibrated against existing solutions, as discussed in Section 2.3.