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Research Paper

Undrained uplift capacity of deeply embedded strip anchors in non-uniform soil

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ABSTRACT

This paper presents new theoretical predictions of the undrained uplift capacity of deeply embedded inclined strip anchors in a soil stratum with a linear variation of strength with depth. Rigorous bounds on the theoretical uplift capacity are presented using upper and lower bound limit analysis. The effects of the strength gradient on the normalized uplift capacity and the predicted failure mechanisms are analyzed. Overall, the effect of the strength gradient on the capacity is shown to be rather small (less than 16% for the range of strength gradients considered), while the influence of the gradient on the failure mechanism can be significant. It is shown that the coupled effects of anchor inclination and the strength gradient are well characterized by formulae that provide a simple means for refining uplift calculations in practical applications.

1. Introduction

Plate anchors are routinely used as foundations for resisting uplift and horizontal pullout forces. For example, they are often implemented in offshore applications to anchor platforms and floating structures to the seabed. Onshore, plate anchors are used to support guy wires for communication and transmission towers, and they are often placed behind retaining walls to act as tiebacks.

Short-term and long-term stability are considerations of paramount importance in the design of plate anchors. Accordingly, numerous methods for predicting the ultimate uplift (pullout) capacity with varying anchor types and soil conditions have been proposed. Most approaches are empirical and revolve around data obtained from laboratory model tests [1–9]. Theoretical solutions have been developed based on limit equilibrium methods [10–13], finite element methods [14–22], cavity expansion theory [23] and limit analysis [4,22,24–30]. Due to wide variations in the soil type, anchor shape, contact conditions, embedment depth, anchor inclination, and loading type, rigorous theoretical approaches for predicting uplift capacity have been slow to replace empirical methods.

The majority of previous studies assume uniform strength throughout the soil mass in which the anchor is embedded, but the profile of shear strength is often non-uniform. The need to develop solutions for a non-uniform strength profile is perhaps best reflected in the study by O'Neill et al. [22], who focus on the performance of drag anchors in clays. In this work and those to follow (e.g., [31–33]), pullout capacity is evaluated simply by averaging the soil strength in the region adjacent to the anchor and then relying on theoretical predictions obtained for a uniform strength profile. In the words of the original study [22], "this is clearly a simplification, and refinement will be needed in the future…to take account of variations of soil strength with depth in a more rigorous fashion." While some previous studies analyze the case where strength increases linearly with depth [16,17,26], no analytical solutions for the uplift capacity of deeply embedded anchors have been proposed. The finite element analyses completed by Yu et al. [16] include deeply embedded vertical and horizontal anchors, but the coupled effects of anchor inclination and the strength gradient for a deep anchor at arbitrary inclination are not addressed.

This paper presents a rigorous analysis of the undrained uplift capacity of inclined, deeply embedded anchors in stratum of soil for which the shear strength varies linearly with depth. Within the framework of limit analysis [34], newly derived semi-analytical upper bound solutions are compared with numerical results obtained using a recently developed upper bound numerical approach known as the "block set mechanism" [35,36] as well as lower and upper bound finite element limit analysis

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(FELA). Tacit assumptions are that the material is perfectly plastic and obeys the Tresca yield criterion. Plain strain is also assumed, and therefore attention is restricted to the case of thin rectangular strip anchors, for which the length greatly exceeds the width. For simplicity, both the anchor and the soil are considered to be weightless, recognizing that the influence of soil weight is minimal for undrained analysis of deeply embedded anchors. The analysis provides verified equations for use in geotechnical design, and it lends insights into the coupled effects of anchor inclination and the strength gradient on the normalized uplift capacity and shape of the failure mechanism.

2. Problem definition

Fig. 1 shows a schematic of the problem analyzed in this study. The anchor's width is denoted by B, and its thickness is taken to be negligibly small. The width B is also assumed to be much smaller than the anchor's depth of embedment, such that the collapse mechanism does not extend to the surface. The anchor is inclined at angle α from the horizontal. At the two interfaces between the anchor and the soil, two types of contact are considered: perfectly smooth (frictionless) and perfectly rough (adhesion equal to the undrained shear strength). The direction of loading is taken to be perpendicular to the anchor, and the major unknown is the force per unit width on the anchor at collapse, i.e., the ultimate load, denoted by Q_u. It is assumed that soil remains in contact with the anchor on both interfaces and that tensile stresses are permitted to develop (i.e., no breakaway). The undrained shear strength c_u is given by

$$c_u = c_{u0} + \rho z \tag{1}$$

where z is depth, ρ is the strength gradient ($\rho \geq 0$), and c_{u0} is the undrained shear strength at the datum $z = 0$. For convenience, the anchor's midpoint (centroid) is selected as the datum $z = 0$. The parameter c_{u0} can therefore be considered as the spatial average of the shear strength in the vicinity of the anchor, and thus the average shear strength defined by O'Neill et al. [22] and others. Dimensional analysis reveals that the problem is characterized by the following dimensionless groups: $Q_u/c_{u0}B$, $\rho B/c_{u0}$, and α. The first of these is N_c, the so-called capacity factor, and this factor is a heretofore unknown function of $\rho B/c_{u0}$ and α:

$$N_c = \frac{Q_u}{c_{u0}B} = f\left(\frac{\rho B}{c_{u0}}, \alpha\right) \tag{2}$$

The dimensionless strength gradient, $\rho B/c_{u0}$, is considered to vary between $0 \leqslant \rho B/c_{u0} \leqslant 0.3$. This range is based on typical values (cf. [37,38]) as well as the physical limitation that the strength cannot be less than zero in the vicinity of the anchor. The analysis focuses on $0° \leqslant \alpha \leqslant 90°$, although the methods and results can be readily extended to the full range $0° \leqslant \alpha \leqslant 360°$, which includes scenarios involving failure in bearing rather than uplift.

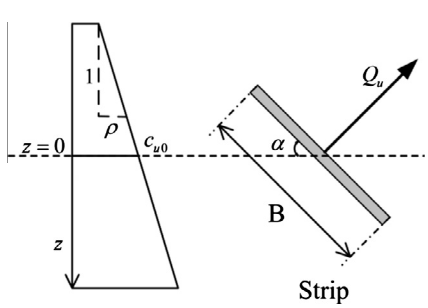

Fig. 1. Problem definition.

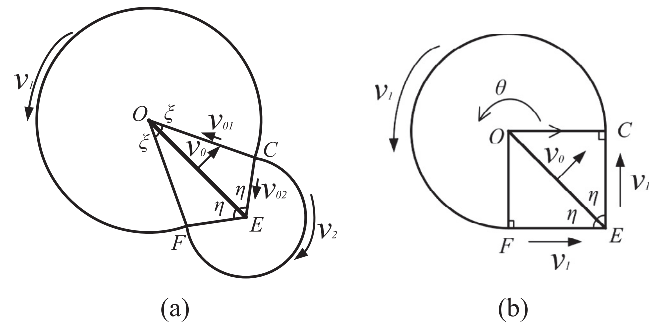

Fig. 2. Upper bound mechanisms for a deeply embedded strip anchor: (a) perfectly rough and (b) perfectly smooth.

3. Limit analysis

Three different limit analysis techniques are used to analyze the problem defined in Section 2: (1) a semi-analytical approach based on upper bound limit analysis, (2) the block set mechanism proposed by Yu et al. [35,36], which is also based on upper bound limit analysis, and (3) lower and upper bound finite element limit analysis (FELA). Upper bound limit analysis rests on consideration of kinematically admissible velocity fields (collapse mechanisms), and it rigorously brackets the true ultimate load from above for loads inducing collapse. Lower bound limit analysis considers statically admissible stress fields as a means of bounding the true ultimate load from below. Additional details regarding limit analysis are described in the comprehensive monograph by Chen [34].

3.1. Semi-analytical approach

Solutions for the unknown function f in Eq. (2) can be obtained within the framework of upper bound limit analysis by postulating the kinematically admissible collapse mechanisms shown in Fig. 2. In both cases, the anchor moves with velocity v_0 normal to the anchor surface. The first mechanism, shown in Fig. 2(a), is applicable to rough anchors, and it consists of two regions that move as rigid bodies together with the anchor (*OCE* and *OFE*) and two zones of continuous shear bounded by circular arcs (*OFC* and *ECF*). The second mechanism, shown in Fig. 2(b), is valid for smooth anchors, and it involves two rigid regions that slide relative to the anchor (*OCE* and *OFE*) and only one zone of continuous shear (*OFC*). Both mechanisms can be considered extensions of the one analyzed by Rowe [4], depicted in Fig. 3(a), to compute upper bounds on the uplift capacity in uniform soil. Rowe [4] indicated that the failure mechanism for a rough anchor is also applicable to smooth strip anchors, and indeed Meyerhof [39] earlier showed using the method of characteristics that the capacity factor $N_c = 3\pi + 2$ is independent of the contact conditions. For uniform soil, the same ultimate load is in fact obtained for each of the three different mechanisms shown in Fig. 3, although the mechanisms for the smooth anchor are valid only when relative sliding is permitted at the soil-anchor interfaces. For non-uniform soil characterized by a strength gradient, each of the mechanisms depicted in Fig. 3 gives different values for the ultimate load. Moreover, more accurate (smaller) upper bounds are obtained for the mechanisms shown in Fig. 2, which permit variation in the shape through the angles ξ and η.

The full derivation of the capacity factors computed based on the mechanisms shown in Fig. 2 is provided in Appendices A and B. Based on the mechanism shown in Fig. 2(a), the analytical upper bound solution for a rough anchor is given by