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Research Paper

Undrained capacity of a surface circular foundation under fully three-dimensional loading

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ABSTRACT

Circular foundations are widely employed in offshore engineering to support facilities and are generally subjected to fully three-dimensional loading due to the harsh offshore environmental load and complex operational loads. The undrained capacity of surface circular foundations on soil with varying strength profiles and under fully three-dimensional loading is investigated and presented in the form of failure envelopes that obtained from finite element analyses. The combined ultimate limit state of circular foundations is defined as the two-dimensional failure envelopes in resultant H-M loading space accounting for the vertical load and torsion mobilisation. The effects of vertical load and torsion mobilisation, soil shear strength heterogeneity and loading angle from moment to horizontal load on the shape of normalised H-M failure envelopes are explored. A series of expressions are proposed to describe the shape of failure envelopes obtained numerically, enabling essentially instantaneous generation of failure envelopes and optimisation of a circular foundation design based on constraint of any input variable through implementation in an automated calculation tool. An example application is ultimately provided to illustrate how the proposed expressions may be used in practice.

1. Introduction

Shallow foundations are extensively employed to support offshore facilities, such as oil and gas platforms, subsea production infrastructures and wind turbines. The traditional design method presented in the industry recommended practices (e.g., API [1]; ISO [2]) for offshore shallow foundations is similar to that in onshore design guideline (Eurocode 7 [3]). Despite the obvious differences between offshore and onshore foundation types and loading conditions, they are both based on solutions for the uniaxial vertical capacity of surface strip foundation on Tresca soil with constant [4] and linearly increasing [5] shear strength with depth and extended with modification factors to account for load orientation, foundation geometry and embedment. In the field, offshore shallow foundations are subjected to significant horizontal load H and moment M along with vertical load V due to the harsh environmental conditions (i.e., wind, wave and current forces) and generally under combined V-H-M loading. Therefore, the traditional method [1,2], which focuses on vertical bearing capacity without explicit consideration of the independent load components, is not well suited to automated iteration for design of offshore shallow foundations. Further, the generally conservative solution may arise due to its simple linear superposition of various modification factors [6].

Alternatively, the ‘failure envelope’ approach has been recommended in API (2011) Annex [1] to capture the ultimate capacity of foundations under combined loading, which can explicitly consider the independent load components, foundation shape and soil strength profile rather than superposing modification factors. Failure envelopes for shallow foundations under combined V-H-M loading have been derived for various foundation geometries and soil conditions (e.g., strip foundations [7,8]; circular foundations [9–12]; rectangular foundations [13,14]). However, a considerable obstacle to their application in design lies in the difficulty to propose a closed-form expression due to the complex interaction of vertical, horizontal and moment loads. Despite expressions having been proposed [7,9,11,13], all of these expressions neglect the effect of vertical load mobilisation on the shape of envelopes. Gourvenec [10] determined that the influence of vertical load mobilisation on the shape of envelopes is considerable, and increases with the increasing level of vertical load.

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In the field, shallow foundations are generally subjected to fully three-dimensional loading (Fig. 1) resulting from the complex environmental and operational loads. The torsion T can be mobilised by eccentric horizontal load with respect to the load reference point, and the moment M can be respectively mobilised by eccentric horizontal and vertical loads, resulting in the non-planar horizontal and moment loading. If the moment mobilised by eccentric horizontal load M_1 and the moment mobilised by eccentric vertical load M_2 are not coaxial, the horizontal load H and moment M are not orthogonal. This is a very common case in offshore engineering practise, e.g., a gravity-based structure subjected to significant horizontal load. The published results for failure envelopes for shallow foundations under combined loading are mostly based on the condition of planar V-H-M loading; that is, the vertical, horizontal loads and moment act in a single vertical plane, without investigating the effect of torsion and loading angle from moment to horizontal load. The undrained load-carrying capacity of rectangular foundations under fully three-dimensional loading has been systematically studied by Feng et al. [13] and Shen et al. [14], yielding expressions for two-dimensional failure envelopes of the resultant horizontal and moment loading with allowance for torsion effects. Sparse literature studies have explored the capacity of circular foundation under fully three-dimensional loading. Finnie and Morgan [15] and Abyaneh et al. [16], respectively, explore the torsion effect on sliding and moment resistance for circular foundations but only in the two-dimensional H-T and M-T loading plane rather than in the fully three-dimensional V-H-M-T loading space.

In this study, finite element (FE) analyses are carried out to investigate the undrained load-carrying capacity of circular foundations under fully three-dimensional V-H-M-T loading and on deposits with different degrees of strength heterogeneity. The framework of this paper is established based on that constructed by Feng et al. [13]. Algebraic expressions are ultimately proposed to describe the failure envelopes of circular foundation on soil with varying strength profiles.

2. Finite element model

2.1. Geometry and mesh

All the FE analyses were conducted using the software ABAQUS [17]. A surface circular foundation of diameter D resting on undrained deposit was modelled. A half-view of the three-dimensional FE mesh is presented in Fig. 2 to clearly show the mesh discretisation on the central plane through the midpoint of the circular foundation. The mesh boundaries extended a distance of $3D$ from the edges of foundation and $3D$ beneath the foundation, which is sufficiently remote that the failure mechanisms were unaffected. The FE model comprises 23,104 eight-node, brick, hybrid elements (refer to C3D8H in ABAQUS element library). Mesh nodes around the circumference of the soil were constrained to prevent out-of-plane displacement of the vertical face, while those at the base of the mesh were constrained in all three coordinate directions. Relatively fine meshes in the soil were generated in the vicinity of the edges of the circular foundation and immediately below the foundation to precisely capture the failure loads and mechanisms.

2.2. Material properties and interface conditions

The undrained soil behaviour was represented with a linear elastic perfectly plastic constitutive law obeying the Tresca failure criterion. The undrained soil shear strength s_u was assumed to be uniform or increase linearly with depth according to $s_u = s_{u0} + kz$ (Fig. 1), where s_{u0} is the shear strength at the foundation base level and k is the soil shear strength gradient with depth z. The degree of soil strength heterogeneity is denoted as $\kappa = kD/s_{u0}$, varying from 0 (uniform soil) to 10. The Young's modulus of the soil E_u was also supposed to vary linearly with depth, maintaining a constant ratio of $E_u/s_u = 1000$. The Poisson ratio of $\nu = 0.49$ was prescribed to approximate the constant volume response of soil under undrained conditions and thus avoid numerical difficulties. The circular foundation was modelled as a weightless, rigid body, with the load reference point located at the midpoint of the foundation base. The soil-foundation interface was fully bonded (i.e., fully rough in shear with no separation permitted) to provide potential for tensile resistance mobilised by passive suction, which is appropriate for the embedded foundation equipped with 'skirts' under short-term loading. The behaviour of the shallowly embedded foundation was commonly approximated by analysing an idealised surface foundation [7,9,10,18].

2.3. Loading path

The swipe test introduced by Tan [19] has been widely employed to construct failure envelopes for a shallow foundation and has been proven to work well in V-H and V-M loading planes [18]. A swipe test consists of two loading steps. In the first loading step, a given displacement u_1 is imposed on the foundation in direction 1 until the corresponding ultimate load F_{1ult} is achieved. Then, another displacement u_2 is applied in direction 2 following the final state of first loading step until the corresponding ultimate load F_{2ult} is reached, during which the displacement u_1 in direction 1 remains constant. A modified version of the swipe test was suggested by Taiebat and Carter [20]. The difference between the original and modified swipe tests lies in the second loading step. In the modified version the displacement u_1 in the first direction is adjusted to reduce gradually rather than remaining constant. Fig. 3 presents the difference between the swipe test and modified swipe test. In this study, the modified swipe test proposed by Taiebat and Carter [20] was adopted to identify failure envelopes in the V-H, V-M and V-T loading planes. After the failure of a vertically loaded foundation (i.e., the completion of first loading step), the vertical displacement w decreases from its maximum value (downwards positive) to zero according to the cosine function, while the horizontal displacement u, the rotation θ_m or the torsional angle θ_t increases from zero to their maximum values according to the sine function. The comparison of failure envelopes obtained from original and modified swipe tests is provided in the following section.

For combined V-H-M loading, a constant vertical load V was initially imposed to the foundation as a proportion of the vertical capacity and then the displacement-controlled and load-controlled fixed ratio probe tests [18] were employed to investigate H-M failure envelopes at varying levels of vertical load mobilisation. For all other combined loading including torsional load T (i.e., V-H-T, V-M-T, V-H-M-T), (1) a constant vertical load V was initially imposed and remained constant in the following loading steps, (2) a constant torsional load T was applied, (3) a pure horizontal displacement u and pure rotation θ_m were employed, respectively, to detect V-H-T and V-M-T failure envelopes, and the constant-ratio displacement u/θ_m and constant-ratio load H/M were used to construct V-H-M-T failure envelopes.

2.4. Sign conventions and nomenclature

The sign conventions employed in this study, as shown in Fig. 1, follow that proposed by Butterfield et al. [21] for planar V-H-M loading and that employed by Feng et al. [13] for fully three-dimensional loading. The sign of M_y is reversed for ease of comparison, changing from the negative to the positive [13]. The loading angle from moment to horizontal load θ obeys clockwise positive