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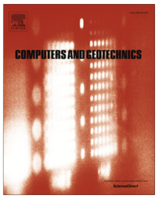

Research Paper

A numerical investigation on the yield surface for shallow foundations embedded in sand

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ABSTRACT

This paper presents a numerical study on the drained response of a shallow foundation subjected to planar combined loads. Plane strain conditions are assumed and different initial foundation depths and values of vertical penetration are considered. Data from centrifuge experiments of surface and buried foundations available in literature, are used to assess the ability of the model to reproduce the essential features of the experimentally observed behaviour. Interpreted within the context of existing work-hardening plasticity models applied to the soil-foundation system and presented in terms of load–displacement curves and load paths, the results of the numerical analyses provide new evidence of the effects of the embedment on the yield surface for a shallow foundation.

1. Introduction

It is now well established that work-hardening plasticity models [1–3] can describe accurately the plastic response of a shallow foundation under planar static combined loads (V, M, H). These models rely on the assumption that, following a given penetration, w, a yield surface develops in the load space. For a foundation of diameter D or breadth B (Fig. 1a) resting on a frictional material, the yield surface can be described by the equation [4]

$$\left(\frac{H}{V_0 h_0}\right)^2 + \left(\frac{M/B}{V_0 m_0}\right)^2 - 2a \cdot \frac{H}{V_0 h_0} \cdot \frac{M/B}{V_0 m_0} - \left[4 \cdot \frac{V}{V_0} \cdot \left(1 - \frac{V}{V_0}\right)\right]^2 = 0 \qquad (1)$$

which is a cigar-shaped envelope, parabolic in sections containing the axis of vertical load (V, M/BH) and elliptical in planes at constant vertical load (H, M/B). Parameters m_0 and h_0 provide the maximum moment and horizontal dimension of the surface, while parameter *a* defines the rotation of its elliptical sections, as displayed in Fig. 1b. According to Eq. (1), the yield surface scales with V_0, the vertical load mobilised by the plastic component of penetration, while maintaining its shape unvaried. Single gravity and centrifuge experimental campaigns have shown that this framework essentially holds for foundations resting on the surface of homogeneous sandy samples [4–6].

The effects of the foundation embedment on the yield surface, as mobilised by the foundation penetration, w, or initial depth, d, and typically up to the foundation breadth (or diameter), have been addressed since the end of the nineties, mostly based on experimental observations.

For a shallow foundation resting on the surface of a loose sand sample, the maximum horizontal dimension of the normalised yield surface (Eq. (1)) was shown to increase linearly as a function of the sole penetration, w [7]. This trend was also observed on medium dense sand samples [8]. Results of tests on buried foundations on very dense sand showed that the size of the normalised yield surface expands following a linear trend as sole function of the initial foundation depth, d, along both the horizontal and moment dimension, with a similar rate [9]. Experiments on flat plates provided with peripheral skirts on dense sand [10], showed that the size parameters, while increasing with the skirts depth, d, also decreases as a function of V_0, reaching a minimum at the maximum allowable vertical load, V_{peak}. A significant influence of the effects of the skirts on the yield surface rotation (parameter *a*) was also observed in the study. An increase in the normalised yield surface size and rotation due to the presence of skirts about the foundation perimeter was also observed in loose sand [11]. These tests also showed that, in presence of very low values of vertical load, the normalised yield surface might extend in the tensile range of vertical load, a tendency also observed more recently on dense sand [12]. Results of centrifuge tests on buried foundations in sand samples of medium density displayed a normalised yield surface function of the foundation initial depth, d, and penetration,

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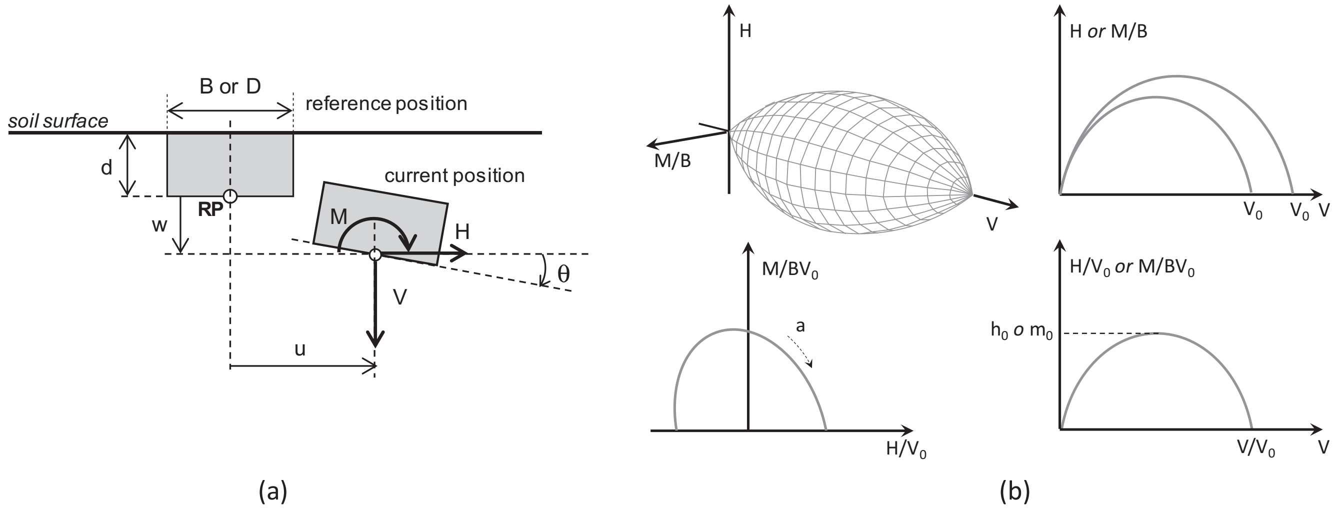

Fig. 1. Combined loading capacity of a shallow foundation: (a) problem position and (b) schematic representation of the yield surface after [24,27].

w [13]. In the tests, a rather large normalised yield surface, established at low values of penetration ($w/D < 0.05$), was observed to quickly reduce as the penetration increased (up to $w/D \sim 0.1$) to resume its expansion at higher penetrations ($w/D > 0.1$). This trend was attributed to a response dominated by the soil dilatancy at low confining stresses and by the foundation embedment at comparatively larger values of penetration. As the experimental apparatus enabled to explore only a small portion of the yield surface, these effects could not be quantified, although a consistent and clear trend was envisaged.

At present, a general expression for the yield surface for a buried foundation, which takes into account the initial depth and the foundation penetration, which is not related to the definition of V_{peak}, is notably absent. This provides the motivation of this study which aims at exploring the yield surface for a shallow foundation, across a practical range of depth and penetration values, using a simple numerical model, suitably developed and validated based on experimental data available in literature [13].

The use of numerical models to investigate the undrained combined bearing capacity of surface embedded foundations dates back to the end of the nineties [14] and is now well consolidated [15–17]. Besides, numerical investigation on the drained combined capacity of an embedded foundation are more recent and relevant to specific cases of study, such as mono-caisson for offshore wind turbines [18] or bridge piers ($d/D > 1$) [19]. Within the context of work-hardening plasticity models, numerical investigation have concerned so far analyses of strip surface and buried foundations under pure eccentric and pure inclined loads [20–22]. However, in these preliminary studies, the ability of the model in capturing the essential features of the foundation behaviour was not assessed by comparison with experimental observations. A numerical work, which proved the ability of a simple finite element (FE) model to capture some aspects of the experimentally observed behaviour of a buried foundation was presented in [23] and provides the starting point of this study. In this study, the validation of this FE model is extended further in presence of various load paths, M/BH, depths of initial burial, d/B, and vertical load mobilisation, V_0. The FE model is then used to explore the effects of the embedment on the yield surface of a buried foundation. Three depths of initial burial ($d/B = 0$, 0.5, 1), two values of penetration ($w/B = 0.1$, 0.2) along several load paths are considered, for surface and buried foundations which fail according to a punching-shear mode under pure vertical load. The applicability of Eq. (1) to the numerical results is thus assessed and the size and rotation parameters are calibrated and expressed as function of d and w. Results find application across a wide range of case in which a buried foundation is subjected to general loading conditions [24–26].

2. Details of the numerical study

Two-dimensional, large-strain finite element analyses (FEA) were carried out to model the long-term, planar combined loading response of a shallow foundation. To the scope, the commercial software Abaqus was used [28]. The effectiveness of the modelling choices, which moved from those introduced and discussed in the work presented in [23], were validated based on selected results of a set of centrifuge tests of buried footings on medium dense silica sand samples. These tests, all presented and interpreted in a recent publication [13], provided the experimental reference for the numerical study.

2.1. Soil and foundation properties

The foundations were of breadth B, initial depth $d/B = 0$, 0.5 and 1 and modelled as solid rigid bodies. The interface between the foundations and the soil was prescribed as fully rough in shear. As depicted in Fig. 2, the mesh boundaries were placed at a distance of 5B from either side of the foundation and 5B from the soil surface. The soil was discretised by four node, bi-linear, plane strain, reduced integration, continuum elements (CPE4R) and modelled as an elasto-plastic material yielding according to the Mohr Coloumb failure criterion. Four nodes elements were used, as convergence issues were observed due to strong mesh deformations, using more accurate eight nodes elements in combination with large-strain analyses [28]. Previous numerical studies, which has considered shallow foundations on a Mohr Coulomb material, have shown the approach to be effective for general loading problems of a foundation, yielding results consistent with experimental data [18,23] or in agreement with more sophisticated constitutive models [19]. Plane strain conditions were considered for simplicity, as the foundation shape was shown to have negligible effects in presence of planar combined loading conditions [9]. Elasto-plastic model parameters ($E = 40$ MPa, $\nu = 0.3$, $\phi' = 30°$, $\psi = 5°$, $\gamma' = 10$ kN/m^3, $c' = 1$ kPa) were selected to provide an overall satisfactory agreement to the centrifuge data. Although with a slightly lower value ψ, the parameters were also shown to essentially fit the results of drained triaxial compression tests ($R_D = 40.5\%$, $p'_0 = 50$, 300 kPa), carried out on the silica sand used in the experiments, as shown in Fig. 3, where the elastic modulus was $E = 25$, 45 MPa for $p'_0 = 50$, 300 kPa respectively.

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