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Numerical modelling of seepage beneath skirted foundations subjected to vertical uplift

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ABSTRACT

This study reports the results of small strain finite element analyses undertaken to determine the rate of displacement of skirted foundations subjected to uplift loading, due to combined swelling and seepage. Compatibility of foundation movement with cumulative seepage of water into the skirt compartment is modelled using a layer of soft poroelastic material immediately below the foundation top plate. Performance of the model is first assessed for a range of stiffness values for the soft layer. The model is then used to investigate the rate of displacement for skirt depths ranging from 0.1 to 1 times the foundation diameter. The results are compared with available theoretical solutions and experimental results, and expressions are provided for calculating the equivalent seepage lengths and resulting uplift velocities. The effect on the seepage behaviour of the presence of a gap down the external skirt–soil interface is also discussed.

1. Introduction

Skirted foundations are shallow foundations, which consist of a plate resting on the soil surface and a peripheral skirt (often supplemented by internal skirts) penetrating into the soil. The skirts encapsulate soft soil near the seabed surface, improving the load-carrying capacity of the foundation by forcing the failure deeper, generally into stronger soil. Skirted foundations are widely used for shallow and deep water oil and gas developments, where they may be required to resist uplift loads or significant overturning moments. A sealed skirted foundation resists uplift by generating negative excess pore pressure, often referred to as suction (relative to ambient water pressure), between the underside of the foundation top plate and the confined soil (referred to here as the 'soil plug') within the skirts. The pressure differential sets up seepage flow into and through the soil plug from the surrounding soil and free water at the soil surface. Water accumulates beneath the foundation top plate, allowing the foundation to move upwards at a steady rate, compounded initially by some swelling of the soil within and below the soil plug (see Fig. 1).

Various experimental studies have presented the time–displacement response of skirted foundations and suction caissons [1,2,3]. The studies show that the response is bilinear with the initial portion corresponding to immediate displacement due to the applied load followed by time–dependent displacement due to the flow of water into the skirt compartment. Some numerical simulations [4,5,6,7,1] have also considered the uplift load behaviour of skirted foundations and suction caissons. The simulations were mainly used to quantify the pullout capacity of the foundation and negative pore pressure development and dissipation underneath the foundation top plate. Seepage and the time–displacement response in uplift of skirted foundations in clay have not previously been studied numerically, although some studies have been reported for skirted foundations in sand [8,9].

Numerical studies have considered the consolidation response of skirted and embedded foundations in clay, under compressive loading, quantifying the displacements and pore pressure dissipation for a range of foundation geometries [10,11]. These studies were based on small strain finite element analysis, with the soil modelled as an isotropic elastic material undergoing Biot-type consolidation. The foundation embedment ratio and skirt–soil interface friction were found to have a significant influence on the consolidation behaviour and hence the foundation settlement.

Seepage flow is only an issue for foundations loaded in uplift. Seepage flow does not occur for skirted foundations loaded in compression, unless free water remains trapped beneath the foundation top plate at the end of installation. Leaving that aside, the soil beneath the foundation undergoes consolidation, excess pore pressures gradually dissipate and the foundation settlement converges towards a long-term value. In uplift, there are three contributions to foundation displacement: an immediate elastic displacement due to the applied load; a time-dependent but transient response to swelling of the soil within and below the skirt compartment; and a steady rate of displacement due to seepage of water into the region beneath the top plate. Provided the uplift

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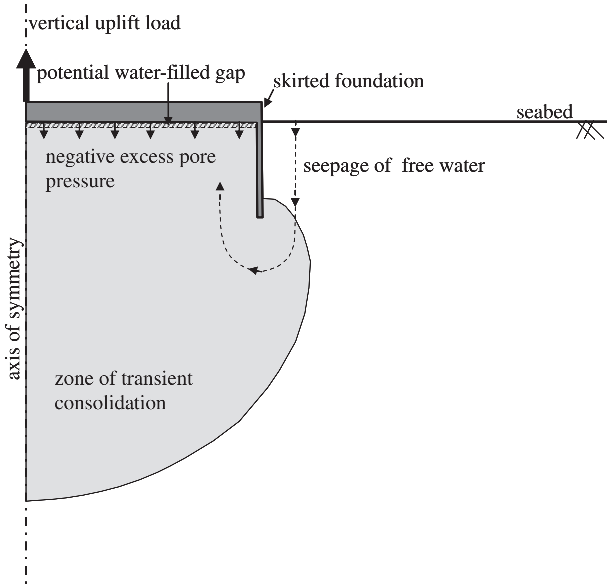

Fig. 1. Schematic of a skirted foundation subjected to vertical uplift loading.

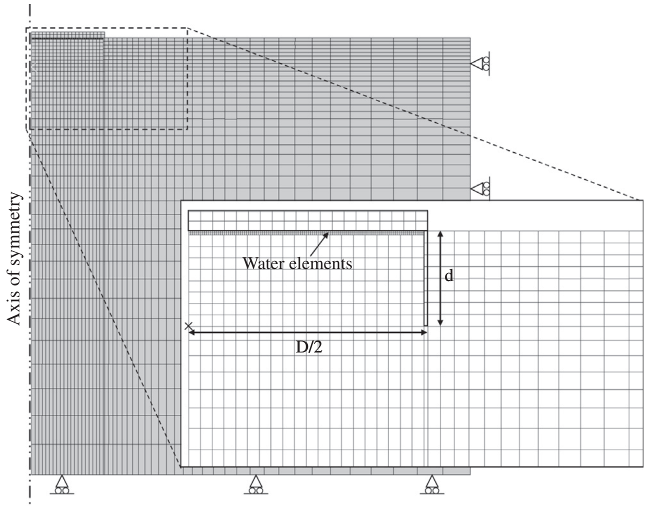

Fig. 2. Finite element mesh used for the study.

load exceeds friction between the skirt wall and the soil, the foundation will continue to move upwards, gradually accelerating due to the decreasing penetration of the skirts within the soil until failure occurs.

The rate of displacement will increase if there is a gap present between the skirt wall and the surrounding soil, due to the increased proximity of free water to the skirt compartment. Experimental studies of the effect of a gap on the time–displacement response of skirted foundations have indicated large increases in displacement [12,3].

In this paper, seepage of water into the skirt compartment of shallow skirted foundations subjected to vertical uplift has been modelled using small strain (i.e. without updating of mesh coordinates) finite element analysis. The analyses were performed for an isotropic elastic half space, following Gourvenec and Randolph [10,11], but with a layer of soft poroelastic 'water' elements introduced immediately below the foundation top plate similar to the approach adopted by Cao et al. [5]. The effect of a gap down the external skirt–soil interface was also studied. The results are compared with available theoretical and experimental results for validation of the model.

2. Finite element modelling

Small strain finite element analyses were performed using commercial software Abaqus [13]. Fig. 2 shows a typical finite element mesh used for this study. The model comprises a rigid skirted foundation, homogeneous isotropic soil and a thin layer of 'water' elements between the underside of the foundation top plate and the confined soil plug.

The water elements were used to ensure uniform negative pore pressure underneath the top plate and to provide compatibility between the foundation displacements and cumulative seepage into the skirt compartment. Previous studies have also considered the presence of a layer of trapped water between the foundation top plate and the soil plug in the finite element model, but only to quantify the undrained pullout capacity of the skirted foundations rather than to model seepage. Zdravkovic et al. [4] used a string of interface elements with very low shear stiffness and very high normal stiffness while Cao et al. [5] used very soft poroelastic elements to represent the water. An approach similar to the latter has been adopted here, with soft (two-phase) poroelastic elements used to model the accumulating water; a parametric study was performed initially to validate the performance of the elements and to choose an appropriate stiffness.

All the analyses were performed on axisymmetric models, representing the behaviour of circular skirted foundations subjected to pure axial vertical loading.

2.1. Loading and drainage

The analyses were performed in two stages: a loading stage and a swelling-seepage stage. In the loading stage, a vertical uplift load was applied to the top plate of the rigid skirted foundation in a single step over a short period of time. During this stage no drainage was allowed and negative excess pore pressures corresponding to the applied pressure were set up around the foundation. After the undrained loading stage, a zero excess pore pressure drainage boundary was specified around the foundation to model the continuous percolation of free water into the soil, and dissipation of the negative excess pore pressures developed.

Two different drainage boundaries were considered: one with drainage allowed along the top surface of the soil surrounding the foundation; and one with drainage allowed also along the soil outside the skirt wall and below the skirt tip in addition to the top surface of the surrounding soil. The first case represents the drainage behaviour of a foundation with 'intact' skirt–soil interface while the second represents a foundation with a 'gap' between the outer surface of the skirt wall and the soil, with free water present in the gap.

The choice of initial time step after loading is an important issue when drainage is considered in a numerical analysis. The time step and element size are related such that immediately after a drainage boundary condition is changed and flow is allowed, sufficient time is permitted for flow through each element. Vermeer and Verruijt [14] proposed a simple expression to calculate the minimum initial time step ($\Delta t_{\min}$) as a function of the element size and properties of the soil skeleton expressed as,

$$\Delta t_{\min} \geq h^2 \frac{\gamma_w}{6Ek} \tag{1}$$

where h is the distance between the nodes of the elements in the region where drainage occurs (in this study, the vertical thickness of the elements adjacent to the skirt was taken), γ_w the unit weight of pore water, and E and k respectively Young's modulus of