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Post-preload undrained uniaxial capacities of skirted circular foundations in clay

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A B S T R A C T

Improvement of the undrained capacities of foundation as a result of preloading, has received attention in offshore engineering only recently. It offers the benefit of optimising foundation design and reducing footprint and cost. This paper investigates the preloading performance of skirted circular foundations in clay using 3D coupled finite-element analyses. The increase in the ultimate undrained uniaxial vertical, horizontal and moment capacities is provided for non-dimensional groups of foundation skirt length, in situ undrained shear strength heterogeneity, magnitude of vertical preload and normalised consolidation time. An exponential relationship between preloading gain in capacity and normalised consolidation time is established, with the maximum preloading gain expressed as a function of the three other dimensionless groups. An approach to estimate the post-preload undrained ultimate uniaxial capacities of skirted circular foundations on normally consolidated clay is ultimately proposed. The influence of foundation geometry is discussed via comparison with the existing solutions.

1. Introduction

Holding vertical load on a foundation in a preloading process improves its capacity due to consolidation and the associated dissipation of excess pore pressures in the soil. In offshore engineering, an ‘active’ preloading process may be used prior to operations to develop an acceptable margin of safety against environmental loading (Randolph and Gourvenec, 2011). Passive preloading, resulting from self-weight consolidation also increases the foundation capacity, though this is usually not considered in design.

The majority of the research work undertaken to date focuses on the enhancement of the vertical undrained bearing capacity of shallow foundations in clay. Fig. 1 summarises the vertical capacity increase $\eta_{v,f}$ after full consolidation for increasing levels of preloading P% (both normalised with the no-preload undrained capacity) from full-scale and reduced-scale experimental work, and from numerical analysis. Lehane and Jardine (2003) conducted field tests to investigate the effect of preloading on the undrained bearing capacity of an embedded solid square foundation in lightly over-consolidated soil (OCR approximately 2.5 at the foundation top level). A significant increase in the undrained capacity ($\eta_{v,f}$ of 1.5) was measured after 11-year of consolidation under a sustained level of preloading of $P\% = 65\%$. A finite-element model was also implemented by Zdravkovic et al. (2003), providing further insight into the response of a preloaded strip foundation in clay with various ratios of over-consolidation (OCR ranging within 1, 2, 4, 9 and 25). A much larger gain in undrained capacity was calculated in normally consolidated clay than in over-consolidated clay. Lehane and Gaudin (2005) reported results of centrifuge testing on embedded solid square foundations. A considerable gain ($\eta_{v,f}$ of 1.8) in undrained capacity was measured after full consolidation under a level of preloading of $P\% = 65\%$, although the over-consolidation ratio (OCR) was approximately 8 at the foundation level. A series of centrifuge tests was conducted by Bienen et al. (2010) to investigate the effects of both preloading and consolidation on the undrained bearing capacity of a surface circular foundation on normally consolidated clay. The results showed an increase ($\eta_{v,f}$ of 1.6) in undrained bearing capacity under a level of preloading of approximately $P\% = 75\%$. As evident from Fig. 1, the improvement in vertical capacity can be significant (up to 80%), but varies greatly as a function of the foundation shape and embedment and the degree of over consolidation of the soil.

More recently, further work has been undertaken to characterise more rigorously the gain in capacity due to preloading. Gourvenec et al. (2014) developed a framework to predict the gain in undrained vertical bearing capacity of a strip and circular foundation as a function of the

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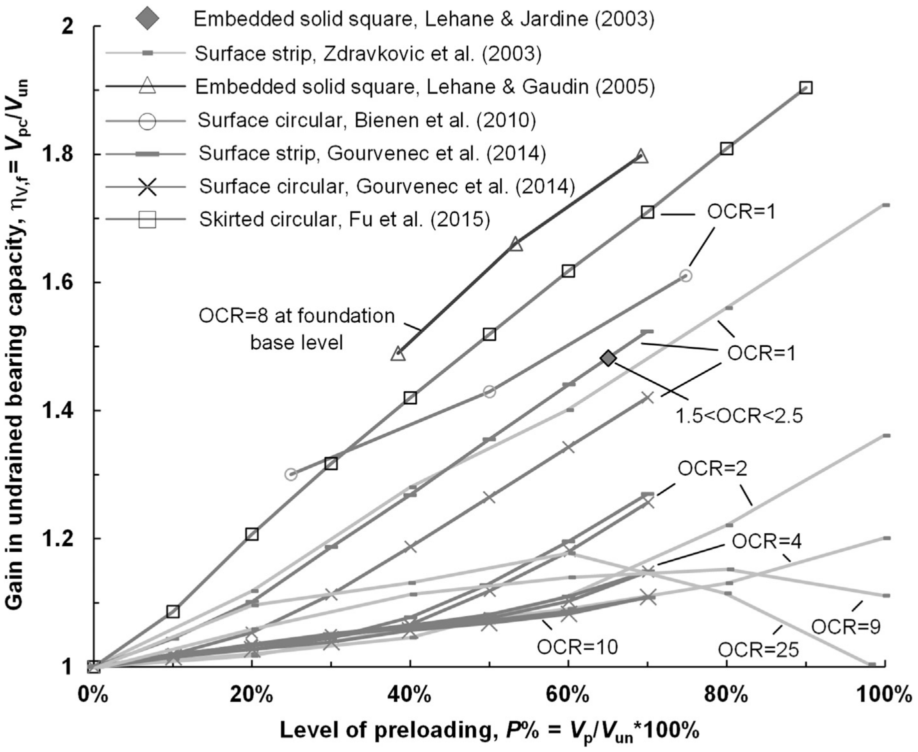

Fig. 1. Summary of published data of increase in undrained bearing capacity of shallow foundations with vertical preloading 10.

level of preloading and degree of consolidation. The changes in preload-driven elastic and plastic stress were assessed to evaluate the gain in average undrained shear strength. In parallel, Fu et al. (2015) conducted a series of centrifuge testing and numerical analyses to investigate the history of the response of the bearing capacity of a skirted circular foundation on soft clay. A time-dependent exponential increase in bearing capacity was proposed for any given level of preloading, based on the evolution in both elastic and plastic volume changes. The effect of the interface property was also investigated, which shows no influence on the gain in undrained bearing capacity, consistent with the observation of Gourvenec et al. (2014).

A smaller body of research investigated the increase in combined vertical (*V*), horizontal (*H*) and Moment (*M*) capacity due to preloading. Bransby (2002) explored the preloaded vertical and horizontal load response of a strip foundation in normally consolidated soil. A higher increase in horizontal capacity was calculated compared with that in vertical capacity. More recently, Feng and Gourvenec (2015) and Vulpe et al. (2016) reported capacity for a surface rectangular (in combined *VHM* as well as the torsional *T* load direction) and for surface strip and circular foundation (in *VHM*) for different levels of preloading and duration of consolidation.

This body of literature provides evidence of the increased foundation capacity due to preloading, and the importance of factors, such as foundation shape, interface property, loading direction, and initial stress state.

However, the influence of the foundation skirt embedment has received less attention. This is of significant importance because the skirt transfers the load applied on the foundation to deeper soil, changing the region of primary consolidation. This particular aspect is addressed in this paper, which presents numerical results using coupled small-strain finite-element analyses to investigate the post-preload capacities of skirted circular foundations on normally consolidated clay. The skirt length, the initial undrained shear strength distribution in the soil, the magnitude of preloading and the duration of consolidation are considered. Based on the finite-element results, formulations to predict the post-preload undrained uniaxial capacities of skirted circular foundations are proposed, as a function of:

Table 1
Soil characteristics for the kaolin clay used in numerical modelling.

Parameters	Values
Slope of critical state line (CSL) in p'-q_d space, M (critical friction angle in triaxial compression, φ'_{tc})	0.890
Void ratio at $p' = 1$ kPa on CSL, e_{cs}	2.140
Virgin compression index, λ	0.205
Swelling and recompression index, κ	0.044
Shear Modulus, G'	$50p'_0$
Submerged unit weight, γ' (kN/m^3)	6
Permeability of soil, k_s (m/s)	1.0×10^{-9}

- the level of preloading *P*%, defined as the ratio of the applied vertical load V_p to the undrained vertical bearing capacity V_{un},
- the duration of application of the preload, defined by the time factor $T_v = c_{v0}t/D^2$ (where c_{v0} is the initial in situ coefficient of consolidation at the skirt tip level, t is the elapsed time and D is the foundation diameter),
- the foundation aspect ratios d/D (where d is the foundation skirt length), which is varied from 0 to 1,
- and the soil strength heterogeneity ratio kD/s_{u0} (where k is the soil strength gradient with soil depth z and s_{u0} is the undrained shear strength at the skirt tip level d), which is varied from 0.5 to 5. Note that, a linear soil strength profile is adopted as $s_u = s_{um} + kz$, where s_{um} is the shear strength at the mudline.

2. Numerical model

2.1. Soil model and parameters

Three-dimensional coupled small-strain finite element analyses were undertaken using the Modified Cam Clay soil model (Roscoe and Burland, 1968), as implemented in Abaqus (Dassault Systèmes, 2010). The soil domain was modelled as a linear elastoplastic material. All