Bearing behaviour of shallow foundations on clays – offshore and onshore, research and practice

Comportement des fondations superficielles sur sols argileux– Recherche et pratiques courantes en géotechnique maritime et terrestre

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ABSTRACT
The paper presents a summary of investigations undertaken to explore shallow foundation response on single and double layer clays in the context of soil flow mechanisms, cavity depth and bearing capacity. Undrained response under concentric vertical loading has been considered. Commonly used design guidelines are assessed against recent results from centrifuge model tests, numerical analysis and closed form solutions including the authors' contributions from offshore applications. Specific attention is focused on the difference between onshore and offshore practice, emphasising fundamental differences in installation techniques.

RÉSUMÉ
Cet article présente une synthèse des recherches menées afin de comprendre le comportement des fondations superficielles reposant sur des sols argileux homogènes et stratifiés à travers les aspects de capacité portante, de mécanismes d'écoulement et de profondeur de cavité. Les chargements verticaux concentriques non drainés sont considérés. Les pratiques courantes de dimensionnement sont évaluées à partir d'essais en centrifugeuse, d'analyses numériques et d'analyses limites, incluant notamment certaines contributions des auteurs dans le domaine de la géotechnique maritime. Une attention particulière est portée aux différences entre les méthodes de dimensionnement de géotechnique maritime et terrestre et tout particulièrement sur les différences fondamentales entre les techniques d'installation.

Keywords : bearing capacity, shallow foundations, offshore, onshore, non-homogeneous clay, stiff-over-soft clay

1 INTRODUCTION

The capacity of shallow foundations on clay is fundamental to much of civil engineering and is generally based on classical solutions for strip foundations together with various adjustment factors. In reality, foundations are more typically of low aspect ratio in plan and are often better represented as square or circular. In particular there are a number of designs of offshore foundations where the foundation can be treated approximately as a large circular footing, for instance some gravity bases for concrete platforms, the spudcan foundations of jack-up units, and the more recently developed caisson or skirted foundations. In most cases the footing is not placed at the ground surface, and it is important to take into account the depth of embedment and also the soil strength gradient and any significant layering.

This paper presents a review that summarises some of the developments in recent years in the context of soil flow mechanisms, cavity depth and bearing capacity for shallow circular foundations. The focus here is on calculation of the bearing capacity of foundations, dividing them into two categories: (a) pre-embedded foundations, which include onshore foundations and offshore gravity bases and skirted foundations; and (b) continuously penetrating foundations such as spudcan foundations. For the former, a footing is placed at the base of a pre-excavated cavity (or on the soil surface) or skirts are used to transfer the bearing surface to below the soil surface. The surrounding soils therefore remain relatively intact, except for minor effects due to excavation or local disturbance due to penetration of the skirts. Design calculations involve estimation of the vertical bearing capacity at the foundation depth and the displacement required to mobilise that resistance.

By contrast, continually penetrating foundations are initially set on the soil surface and are then pre-loaded under progressively increasing load up to a design maximum. This causes them to undergo progressive penetration into the deposit until the load on the foundation is equilibrated by the resistance of the underlying soil. Therefore, the foundation sits on heavily remoulded (pre-failed) soils and design calculations involve estimating a complete load-penetration profile in order to ascertain the final penetration depth.

2 VERTICAL BEARING CAPACITY

The short term, or undrained, bearing capacity, q_u, of a shallow circular foundation at a specific depth, d, under the action of purely vertical loading can be calculated according to

$$q_u = N_c s_{u0} + \gamma d + \gamma \frac{V}{A} - W_f \qquad (1)$$

where N_c is a dimensionless bearing capacity factor, s_{u0} is the undrained shear strength of the soil (s_u) at the foundation base level, γ is the unit weight of the soil (with effective weight being used where free water exists at the soil surface), V is the volume of the embedded portion of the foundation below the foundation level, A is the largest cross sectional area of the foundation and W_f is any unaccounted weight of the foundation that is not part of the structural loading.

Appropriate design approaches or calculation methods are the cornerstones for accurate estimation of bearing capacity, but unfortunately uncertainty exists in selection of appropriate values for N_c and s_u. The paper provides specific guidance on the former, while for the latter it is suggested that the design shear strength should be based on the average of values relevant for different modes of shearing (e.g. triaxial compression, triaxial extension and simple shear). Some spatial averaging for s_{u0} may be appropriate, but this should be symmetric above and below the foundation level, so that s_{u0} essentially represents the local shear strength at the level of the foundation base.

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The paper addresses two main configurations of clay deposits: (a) single layer with strength increasing with depth and (b) double layer with stiff-over-soft strength profile. Commonly used design guidelines are compared with recently published results from closed form solutions, centrifuge model tests and numerical analysis and improved design approaches are suggested for both pre-embedded and continuously penetrating circular foundations.

3 PRE-EMBEDDED FOUNDATIONS

3.1 *Single layer clay*

For relatively uniform clay deposits, the undrained shear strength, s_u, can be idealised as

$$s_u = s_{um} + kz \tag{2}$$

where s_{um} is the soil strength at the surface (or mudline) and k is the rate of increase in s_u with depth z. The effect of the strength gradient may be expressed in terms of a non-homogeneity factor kD/s_{um}. The relative magnitude of shear strength and effective stress, expressed as a normalised strength of $s_{um}/\gamma D$ or k/γ, also affects the bearing response and the maximum cavity depth.

A number of solutions have been published over the last 25 years addressing the bearing capacity of foundations in clay in a rigorous manner. For flat surface foundations (d/D = 0; $s_{u0} = s_{um}$), bearing capacity factors for smooth and rough bases have been given by Salençon & Matar (1982), Houlsby & Wroth (1983), Tani & Craig (1995), Martin (2001), Gourvenec & Randolph (2003) and Houlsby & Martin (2003) for kD/s_{um} ranging from 0 to 20. The values are from plasticity solutions and FE analyses, with exact values for a circular surface foundation plotted in Figure 1.

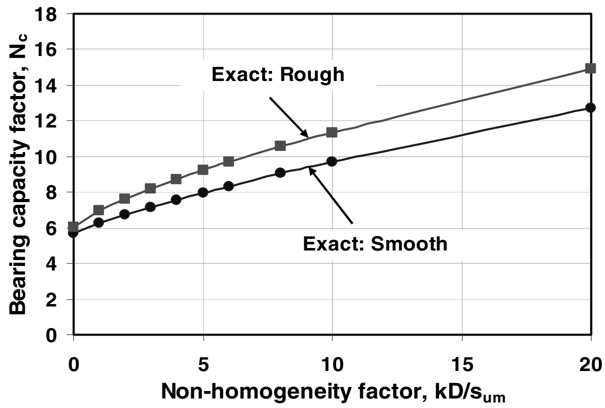

Figure 1. Bearing capacity factors for surface circular foundation for different kD/s_{um}.

For embedded foundations, it is first necessary to excavate a cavity in the deposit. The stability of an unsupported cylindrical cavity has been investigated extensively by Meyerhof (1972) using Rankine's pressure theory, Britto & Kusakabe (1983) implementing upper bound plasticity analysis, and Lyamin & Sloan (2002) employing finite element based upper bound and lower bound analyses. Combining all solutions, and confirming them through additional FE analyses, a robust expression was developed for estimating the critical depth for cavity wall collapse in clay as

$$\frac{H_w}{D} = 9.1\left(\frac{s_{uw}}{\gamma D}\right)^{1.2} \tag{3}$$

where H_w is the cavity depth at which wall failure is initiated and s_{uw} is the soil undrained shear strength at that depth.

The effect of foundation embedment has been explored by Martin (2001), Wang & Carter (2002), Houlsby & Martin (2003), Edwards et al. (2005) and Hossain & Randolph (2009a). Attention here is restricted to foundations modelled as having a smooth or rough base, but smooth sides or no vertical shaft. For embedded foundations, no exact plasticity solutions have been found. Instead, the bracket between lower and upper bounds (Martin 2001) widens rapidly as the relative embedment increases. For $kD/s_{um} = 0$, it was found that the authors' spudcan (included angle 154°) results from FE analysis are in excellent agreement with Wang & Carter's (2002) result from large deformation FE (LDFE, smooth) and Edwards et al.'s (2005) factors from small strain FE (SSFE, rough) (Hossain & Randolph 2009a). However, the widely quoted bearing capacity factors of e.g. Skempton (1951), Houlsby & Martin (2003), as adopted by current design guidelines ISO (2003), are overly conservative compared to the recently published factors from FE and closed form plasticity solutions.

Since all recent FE results converge for full embedment range, simple expressions for the factor for uniform clay, N_{c0}, can be developed based on those results as

$$N_{c0} = 5.69 + \frac{d}{0.26D}\left(1 - \frac{d}{4.9D}\right) \le 10.4 \text{ at } \frac{d}{D} = 2.25 \quad \text{Smooth} \tag{4a}$$

$$N_{c0} = 6.05 + \frac{d}{0.27D}\left(1 - \frac{d}{5.45D}\right) \le 11 \text{ at } \frac{d}{D} = 2.5 \quad \text{Rough} \tag{4b}$$

where d is the depth of the foundation below the ground surface. A transition from general shear to a confined 'cavity expansion' failure mechanism occurs at depths of approximately 2.25D (smooth) and 2.5D (rough).

For non-homogeneous clay with $kD/s_{um} > 0$, Houlsby & Martin's lower bound factors are again conservative. Since, for weightless soil, the results for a spudcan were found to be consistent with those for a flat-based foundation, the depth factors suggested by Hossain & Randolph (2009a) considering a wide range of kD/s_{um} may be applied to onshore practice. The bearing capacity factors may be estimated according to

$$N_c = N_{c0}\left[1 + 0.161\left(\frac{kD}{s_{u0}}\right)^{0.8} \Big/ \left(1 + \frac{d}{D}\right)^{2}\right] \quad \text{Smooth} \tag{5a}$$

$$N_c = N_{c0}\left[1 + 0.191\left(\frac{kD}{s_{u0}}\right)^{0.8} \Big/ \left(1 + \frac{d}{D}\right)^{1.5}\right] \quad \text{Rough} \tag{5b}$$

3.2 *Stiff-over-soft clay: potential for punch-through*

The design of structures founded in a stronger soil layer overlying softer soil is a frequently encountered problem in geomechanics. The potential exists for the structure to punch-through the upper stronger layer. To simplify the problem, the strength for the upper layer may be considered as uniform (s_{ut}) while that for the lower layer may increase with depth according to $s_{ub} = s_{ubs} + k(z-t)$, where t is the original thickness of the stiff layer. For a circular footing on stiff-over-soft clays, Brown & Meyerhof's (1969) approach has been recommended in offshore design guidelines, and widely used by practitioners. More recently the problem has been addressed through finite element analysis, although mostly limited to surface footings (Wang & Carter 2002, Edwards & Potts 2004). All bearing capacity factors ($N_{cl} = q_{max}/s_{ut}$) are for $kD/s_{ubs} = 0$, as shown in Figure 2. By comparison, the Brown & Meyerhof approach (based on results from 1g model tests) provides an unduly conservative estimate of bearing capacity.

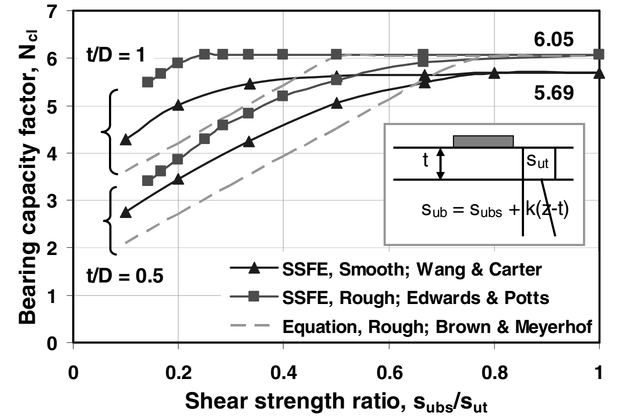

Figure 2. Bearing capacity factor for surface circular foundation on stiff-over-soft clay ($kD/s_{ubs} = 0$).

To explore the influence of foundation embedment and lower layer strength non-homogeneity kD/s_{ubs}, parametric SSFE analyses were undertaken for surface ($d/D = 0$) and embedded ($d/D = 0.5$) foundations for a clay with varying kD/s_{ubs} between 0 and 0.6, for thickness ratio of $t/D = 0.5$ to 1.5. Four values of s_{ubs}/s_{ut} = 0.2, 0.4, 0.6 and 0.8 were examined for each combination of t/D and kD/s_{ubs}. The computed values showed that for an embedded foundation, as for a surface foundation, the bearing capacity factor decreases in a nonlinear manner from a value for uniform clay at corresponding depth as the strength ratio decreases.

The strength non-homogeneity also has substantial influence on the bearing response, hence on the severity and likelihood for punch-through. The bearing capacity for $kD/s_{ubs} > 0$ is always greater than that for $kD/s_{ubs} = 0$ owing to the greater 'average' strength of the lower layer. As such, the severity of punch-through reduces substantially as kD/s_{ubs} increases. For all FE results, the simplest curves which may be fitted to the data yielded the following equation

$$N_{cl} = \left[3\frac{(t - d)}{D} + N_c\left(\frac{s_{ubs}}{s_{ut}}\right)^n\right]\left(1 + \frac{kD}{s_{ubs}}\right)^{0.4} \le N_c \qquad (6)$$

where n = 0.67 (for smooth) or 0.55 (for rough) and N_c is the factor for single layer clay at corresponding depth, d (as calculated from Equation 4).

It should be noted that all previously discussed results are for weightless soil. For pre-embedded foundations, the cohesive bearing capacity may be calculated accurately by adding appropriate surcharge contribution depending on the mobilised soil failure pattern. In Equation 1, the overburden contribution needs to be considered in shallow embedment regime, but the mobilised capacity will be independent of that after attaining a limiting bearing capacity factor.

4 CONTINUOUSLY PENETRATING FOUNDATIONS

The authors have investigated spudcan foundation performance on clays through centrifuge model tests and LDFE analyses by penetrating spudcans continuously from the seabed surface. Two main configurations of clay deposits were explored: (a) single layers with uniform and increasing strength profiles and (b) double layers (stiff-over-soft) with uniform-over-uniform and uniform-over-non-uniform strength profiles. The evolving flow patterns (see insets on Figures 3 and 4) during continuous spudcan penetration leads to complex patterns of soil strength in the vicinity of the spudcan. However, spudcan resistance profiles are generally assessed within the framework used for onshore foundations, with the foundation wished in place at successive depths. The study also showed that the maximum cavity depth, H, above the advancing spudcan is limited by soil back-flow due to the penetration action, and may be estimated by (Hossain & Randolph 2009a)

$$\frac{H}{D} = S^{0.55} - \frac{S}{4} \quad \text{where } S = \left(\frac{s_{um}}{\gamma' D}\right)^{(1-k/\gamma')} \qquad (7)$$

This limit occurs well before that due to cavity wall instability (Equation 3). In the following sub-sections, two practical examples for each soil category explored are discussed.

4.1 *Single layer clay*

Menzies & Roper (2008) reported 13 case histories in the Gulf of Mexico. LDFE analyses have been undertaken for all 13 sites with and without taking strain softening and rate dependency into account. One of these cases will be described here, with the normalised parameters: $s_{um}/\gamma' D = 0.03$; $k/\gamma' = 0.235$; $kD/s_{um} = 7.59$ (see Site 1, Menzies & Roper 2008). Bearing capacity curves from all analyses for $kD/s_{um} = 7.59$ (back-calculated following Equation 1 with V now the embedded spudcan volume) and recorded profiles are shown in Figure 3.

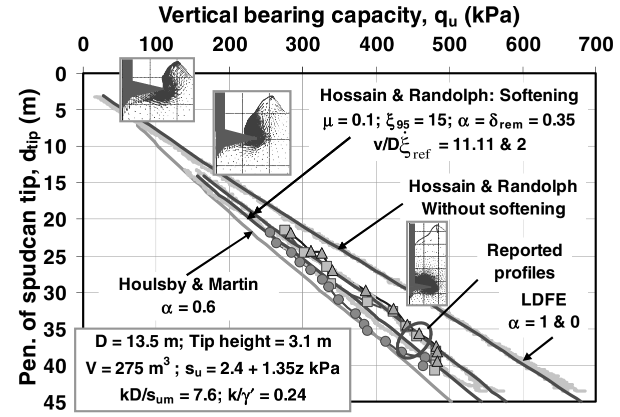

Figure 3. Comparison among LDFE results, Hossain & Randolph approach, SNAME approach and reported field data (single layer clay). [Rate effect: μ is relative strength change per decade of strain rate change; softening: ξ_{95} is cumulative plastic shear strain for 95 % remoulding, δ_{rem} is inverse of soil sensitivity.]

In addition to the LDFE curves, design predictions are shown from (a) the lower bound solutions of Houlsby & Martin (2003) for pre-embedded foundations and (b) the mechanism-based design approach of Hossain & Randolph (2009a). These two solutions are for ideal elastic-perfectly plastic soil. In an attempt to model real soil behaviour more closely, Hossain & Randolph (2009b) proposed adjustment factors as a function of soil sensitivity, ductility and rate dependency. They found that for typical parameters the bearing capacity was reduced by between 15 and 20 %, as shown in Figure 3.

The effect of spudcan base roughness (α) on the bearing response was found to be minimal owing to the presence of softer soil being dragged down with the spudcan during continuous penetration in non-homogeneous clay (Hossain & Randolph 2009a). The recorded full penetration profiles are bracketed by the predicted profiles, which have a tight range of ± 5 % for the spudcan penetration under initial (fast) and final (slow) stages of preloading. This confirms the need to take full account of rate and softening effects in order to achieve accurate predictions for continuously penetrating foundations.

4.2 *Stiff-over-soft clay: potential for punch-through*

The installation of independent-leg jack-up rigs in seabed sediments where a strong layer overlays weaker soil can lead to a catastrophic 'punch-through' event, with potential leg buckling or toppling of the unit. A typical case (t/D = 1, s_{ubs}/s_{ut} = 0.4, $s_{ubs}/\gamma_b D$ = 0.36, kD/s_{ubs} = 0) is discussed below, with comparisons of computed results from LDFE analyses and predictions from the Hossain & Randolph (2009c, d) and SNAME design approaches.

LDFE analyses were performed without (for α = 0 and 1) and with (for μ = 0.1; ξ_{95} = 10, 20; $\delta_{rem} = \alpha$ = 0.25) taking strain softening and rate dependency into account. Figure 4 plots the resulting penetration responses (q_u), as a function of spudcan tip penetration depth.

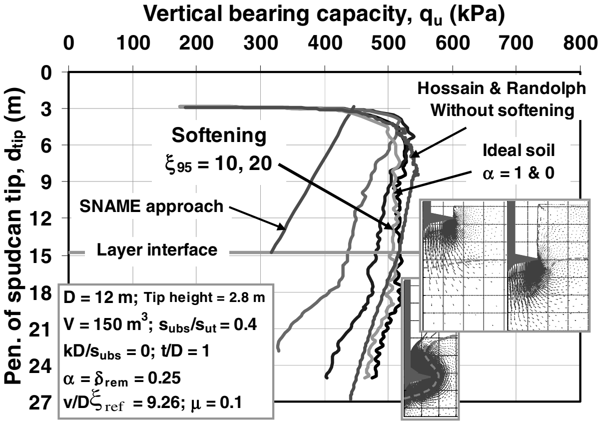

Figure 4. Comparison among LDFE results, Hossain & Randolph approach and SNAME approach (double layer clay).

A plug of 'stiff' material from the upper layer is trapped beneath the spudcan and is pushed down with the advancing spudcan into the lower layer (see inset mechanisms, Figure 4). Consequently, the effect of spudcan base roughness is found to be minimal. A local peak in penetration resistance, resulting in a potential punch-through situation, is exhibited in all cases, but is most pronounced where strain softening is taken into account.

The figure also includes computed load-penetration curves using the Hossain & Randolph (2009c, d) and SNAME design approaches. For assessing spudcan penetration response on stiff-over-soft clay, SNAME (2002) recommends a bearing capacity factor calculated following Brown & Meyerhof (1969), but adjusted for embedment depth by applying a constant depth factor, following the semi-empirical approach of Skempton (1951). The approach does not account for the distortion of the upper layer as it punches through into the lower layer, and indeed provides an unduly conservative estimate of penetration resistance with greater severity of punch-through.

By contrast, Hossain & Randolph's curves closely follow the LDFE results for ideal soil. The approach has also provided excellent prediction for a reported punch-through case history (Hossain & Randolph 2009d).

5 CONCLUDING REMARKS

The paper has summarised traditional design approaches and recently published solutions for evaluating ultimate vertical capacity of onshore and offshore shallow foundations on single and double layer clays. The following conclusions are drawn:

(a) Traditional design approaches were shown to be excessively conservative, as evident from the extensive database of results from finite element analyses and plasticity solutions.

(b) For pre-embedded foundations, traditional approaches provide good estimates of bearing capacity for surface footings on relatively uniform clay. However, adjustments are required for embedded foundations, particularly in the case of clay with increasing strength profile and layered clay where the upper layer has significantly higher strength than the lower layer.

(c) Improved design approaches are provided for circular pre-embedded foundations on single layer and stiff-over-soft clays.

(d) Differences in construction technique between offshore (for spudcan) and onshore practice require explicit differences in design methodology for the assessment of bearing resistance at a given penetration (offshore) or embedment (onshore).

(e) For offshore spudcan foundations, recommended design approaches are currently based on inappropriate models of the soil deformation patterns, leading to significant underestimate of the bearing capacity for single layer clays. New design approaches are provided, including approximate allowance for the effects of softening.

(f) On stiff-over-soft clays, traditional approaches give poor estimates of the potential for punch-through failure and its degree of severity. A new design approach has been proposed that fits results from large deformation finite element analyses.

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