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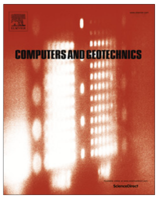

Technical Communication

Bearing capacity of rectangular footings in uniform clay with deep embedment

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ABSTRACT

This letter is concerned with the undrained bearing capacity of rectangular footings with various aspect ratios and embedment ratios in uniform clay. It covers thin plate foundations with low aspect ratios and high embedment depth with embedment ratio up to 150. The work is based on small strain finite element analysis (FEA). After verification of the FEA model against existing solutions of the bearing capacity factors of rectangular footings, a series of FEA results are obtained. Based on the FEA results, a simple formulation is proposed to calculate the bearing capacity factor for rectangle footing with different aspect ratio in any embedment depth, extending the existing solutions to cover a wider ranges of footing aspect ratios and embedment ratios.

1. Introduction

Gravity installed plate anchor (GIPLA) is a newly developed anchor for offshore mooring floating facilities. Its mooring capacity (i.e. uplift resistance) largely depends on its penetration depth during gravity installation [12]. In order to assess the final penetration depth of the anchor after installation, soil resistance needs to be predicted accurately. As part of the soil resistance, the end bearing of the anchor fins (see Fig. 1) is normally calculated based on the bearing capacity formulation of deeply embedded strip foundations [14,10,11].

Eq. (1) shows the general form of footing capacity in undrained uniform clay:

$$q_u = q_0 + s_c d_c N_{c0} s_u = q_0 + N_c s_u \tag{1}$$

where q_u is the ultimate bearing pressure at the footing base; $q_0 = \gamma D$ is the surcharge loading at the footing base; D is the embedment of the footing base from the soil surface; γ is the unit weight of soil; $N_{c0} = \pi + 2$ [15] is the bearing capacity factor of surface strip footing; s_u is the representative undrained shear strength of clay; d_c is embedment depth factor, which is the ratio of the strip footing net bearing at depth D to that for an identical strip footing at the soil surface; s_c is footing shape factor, which is the ratio of the net bearing of a surface footing to that for a surface strip footing; $N_c = q_{net}/s_u$ ($q_{net} = q_u - q_0$) is the net bearing capacity factor of a footing with any shape and embedded in any depth. Eq. (1) implies that the depth and shape factors are independent [16]. However, the bearing capacity factor N_c has taken into account the combined effects of footing aspect ratio and embedment ratio.

Many scholars have studied the ultimate bearing capacity of rectangular footings with different aspect ratios and embedment depths. Table 1 summaries the previous studies on shape and embedment factors (s_c and d_c). It can be observed that the formulations of s_c and d_c are empirical before 1970s, as they are derived from approximate analysis and prototype and model experiments [18,13,20,1]. Due to the uncertainties involved in the empirical formulations, the bearing capacity of footings have been studied recently employing numerical methods, such as method of characteristics (MoC) [19], upper bound analysis (UB) [22], finite element limit analysis (FELA) [16], and finite element analysis (FEA) [7,8,22]. Most of the studies are limited to a relatively shallow embedment (i.e. D/B up to 2.5, where D is embedment depth and B is the diameter of a circular footing or the width of a rectangular footing). Among these research work, Salgado et al. [16], using FELA, conducted a more comprehensive work, which covered the bearing capacity factors for strip, circular and rectangular footings with different aspect ratios and with embedment ratio extended to $D/B = 5$. The footing-soil interface was considered rough and the soil was homogenous clay. Edwards et al. [6], using the Imperial College Finite Element Program, investigated the bearing capacity

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Nomenclature

A	effective area of footing base
B	width of footing base
D	depth from the base of footing to the ground surface
q_u	ultimate unit base resistance
γ	unit weight of clay
γ'	effective unit weight of clay
q_0	surcharge at the base level, calculated by γD
q_{net}	net unit base resistance
N_{c0}	bearing capacity factor of strip footing resting on the surface of clay
s_u	representative undrained shear strength of clay
d_c	depth factor that is the ratio of the net limit unit base resistance for a strip footing at depth D to that for an identical strip footing at the soil surface
s_c	shape factor that is the ratio of the net limit unit base resistance of an any shape footing resting on the soil surface to that for a strip footing on the soil surface
L	length of footing base
F	bearing force without the soil buoyancy acting on the footing base
N_c	bearing capacity factor of footing with different aspect ratio in any embedment depth, calculated by F/s_uA
δ	displacement of footing
μ	Poisson's ratio of clay
E	Young's modulus of clay
I_r	rigidity index of clay, calculated by E/s_u
M	coefficient of bearing capacity factor, calculated by N_c/N_{c0}
c_1, c_2	parameters of M

factors of strip and circular footings in homogenous clay with embedment ratio up to 4 and their results agree well with that by Salgado et al. [16].

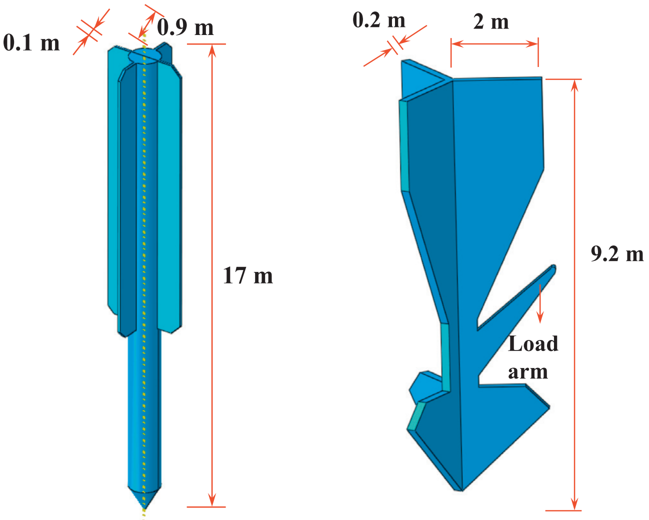

Fig. 1. Typical dimensions of torpedo anchor and GIPLA.

However, the formulas of the bearing capacity of rectangular footing, including the effects of footing aspect ratio and embedment ratio, might not be applicable to the end bearing assessment for the anchor fins (see Fig. 1). In general, the penetration depth of GIPLA is around 10.7–20.1 m, the thickness of the fin is about 0.1–0.2 m and the width of the fin is about 2–3 m [24,17]. This means that the embedment ratio can be as high as about 50–200 and footing aspect ratio can be as low as about 0.03–0.1.

In the present study, the bearing capacity factors (N_c) of rectangular footing are studied with wide ranges of aspect ratios and embedment ratios to extend the existing solutions to cover higher embedment ratios and lower aspect ratios. The commercially available finite-element software ABAQUS [2] is used. The finite element model is validated first with existing bearing capacity results for footings in clay, followed by a series of FE analysis. The FE results obtained can be used to establish a design formula to calculate the bearing capacity factor of a rectangle footing with any aspect ratios (i.e. $B/L = 0–1.0$) and its embedment ratio up to $D/B = 50$.

2. Finite element model

The commercially available FEA software, ABAQUS, was chosen as the computation platform, since it has been used successfully in the computation of footing bearing capacity [7,23]. Small strain finite element models in plane strain and three-dimensional space

Table 1
Summary of published studies about s_c and d_c.

D/B[a]	kB/s_u[b]	Method[c]	d_c	s_c[d]	Authors
$\leqslant 5$	0	SE	$d_c = 1 + 0.2D/B$ ($D/B \leqslant 2.5$) $d_c = 1.5$ ($D/B > 2.5$)	$s_c = 1 + 0.2B/L$	Skempton [18]
$\leqslant 2.5$	0	SE	$d_c = 1 + 0.2D/B$	$s_c = 1 + 0.2B/L$	Meyerhof [13]
$\leqslant 5$	0	SE	After Skempton [18]	1.2 for square and circular	Terzaghi and Peck [20]
$\leqslant 5$	0	SE	$d_c = 1 + 0.4D/B$ ($D/B \leqslant 1.0$) $d_c = 1 + 0.4\mathrm{atan}(D/B)$ ($D/B > 2.5$)	After Skempton [18]	Brinch Hansen [1]
$\leqslant 0.3$	$\leqslant 30$	MoC	$d_c = 1 + \mathrm{n}D/B$ (n varies with kB/s_{um})	s_c is related to kB/s_{um} and D/B (for circular footings)	Tani and Craig [19]
$\leqslant 5$	0	FELA	$d_c = 1 + 0.27(D/B)^{0.5}$	$s_c = 1 + c_1B/L + c_2(D/B)^{0.5}$ (c_1 and c_2 vary with B/L)	Salgado et al. [16]
$\leqslant 1.2$	$\leqslant 5$	UB&FEA	$d_c = 1 + 0.25(D/B)^{0.4}$	–	Yun and Bransby [22]
$\leqslant 1$	0	FEA	$d_c = 1 + 0.86D/B - 0.16(D/B)^2$	$s_c = 1 + 0.214B/L - 0.067(B/L)^2$	Gourvenec et al. [7] Gourvenec [8]

[a] B represents the diameter of circular footing and the width of rectangle footing.

[b] k is the gradient of shear strength with depth in linearly increasing shear strength profile. s_{um} is the shear strength of clay at the mudline.

[c] SE, semi-empirical; MoC, method of characteristics; UB, upper bound; FEA, finite element analysis; FELA, finite element limit analysis.

[d] L represents the length of rectangle footing.