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Effect on Bearing Capacity Factor of Conical Footings on c-ϕ Soil with Linearly Increasing Cohesion

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Abstract: The load from the jack-up rig is transferred into the ground through a spudcan foundation. This spudcan foundation is mostly used in offshore drilling operations. The jack-up rig is usually triangular or rectangular whereas the spudcan is a conical-shaped axisymmetric footing. The effects, of such a footing in a non-homogenous soil, are still sparsely explored in the literature. Therefore, for a conical footing on a non-homogenous soil (with linearly increasing cohesion), the Bearing Capacity Factor (N_c) is presented in the present study using finite element limit analysis. The dimensionless parameters such as internal friction angle (ϕ), cohesion gradient ratio (m), and cone apex angle (β) are considered in this study. It has been observed that the Bearing Capacity Factor increases with the increase in the value of cohesion gradient ratio (m) and internal friction angle (ϕ) whereas decreases with the increase of cone apex angle (β).

Keywords: Bearing Capacity Factor; conical foundation; finite element limit analysis; linearly increasing cohesion.

1 Introduction

Installation of the massive, inverted, conical spudcan footings into fine-grained silt material is troublesome. The industry has always classified installation circumstances as either undrained in 'clays' or drained in 'sands' so either only cohesion is considered or ϕ is considered at a time. Cassidy and Houlsby [1] calculated bearing capacity factors of conical footing whereas Kumar et al. [2] took linearly increasing cohesion soil profile for under-reamed piles and Griffiths and Yu [3] took it for slopes. In this study, both parameters are taken simultaneously so that the analysis can be extended to silt and partially saturated states where both parameters are present simultaneously. The soil taken in the present study was assumed to obey Mohr–Coulomb's failure criterion. This study presents you with the Bearing Capacity Factors (*BCF*) that can be used for soils where cohesion increment with depth is considered.

Spudcans are susceptible to various types of soil conditions as jack-up platforms are mobile platforms. They cannot be designed separately for each type of condition therefore the design of the spudcan has to be done while keeping the variability of soil condition over a large volume of soil in mind.

1.1 Jack-Up Rigs

Offshore drilling in shallow to medium depth water is done in the ocean using mobile drilling platforms known as jack-up rigs. A floatable drilling platform (self-propelled or towed by tugs) with legs that can be moved up and down is known as a mobile jack-up rig. These platforms are generally triangular or square. The depth at which they work is around 100-150m below the water surface. The platform has three legs with three conical footings at the bottom known as spudcans. These foundations penetrate the seabed and thus provide stability to the platform above. In the preloading stage, the spudcan can penetrate to a depth of three times the diameter of the spudcans in soft clay. The diameter of the spudcan is around 10-20 m. The legs are raised when the platform has to be relocated. The legs are lowered and jacked into the seabed to create a foundation, and the once-floating hull raises itself with the help of the settled legs to become an elevated working structure. Before the operations begin, the footings are tested to 100% of their capacity to ensure their performance during a storm or adverse conditions.

1.2 Soil Profile

The soil profile for offshore engineering varies immensely. In many cases, the soil is in layers. These soil layers' shear strengths might vary a lot from each other. Albeit, in this study, the soil profile has been taken to uniform where the cohesion of the soft clay increases linearly with depth.

2 Methodology

2.1 Problem Definition

The diagram of the problem of the conical footing is shown in Fig. 1, where D and β represent the footing diameter and the cone apex angle, respectively. Since the geometry of this problem is a conical shape, the problem can be modelled under axisymmetric conditions. The vertical pressure applied on the conical footing is denoted by Q_u.

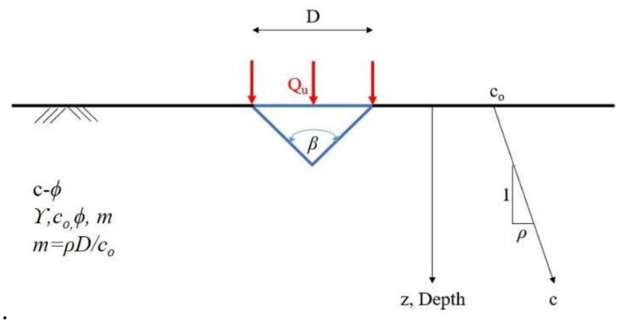

Fig. 1. Problem definition of a conical footing on soil with LIC

The soil is defined as weightless material to neglect the effect of unit weight on the undrained bearing capacity solutions. As the in-situ vertical effective stress in the ground results in an increase in the strength of soil with depth. The linear functions of undrained cohesion increasing with depth can be expressed as in Eq. 1.

$$c(z) = c_o + \rho z \tag{1}$$

where ρ = linear cohesion gradient, $m = \rho D/c_o$ = cohesion gradient ratio, c_o= cohesion on ground surface.

Since the soil is taken as a weightless material the Terzaghi equation for shallow footing is given below

$$Q_u = c_o N_c + q N_q + 0.5\gamma B N_\gamma \tag{2}$$

For weightless soil and no surcharge condition, Eq. 2 will be reduced to

$$Q_u = c_o N_c \tag{3}$$

as $\gamma = 0$. Subsequently, the considerable variables are reduced to three dimensionless input variables after using the dimensionless technique by Butterfield [4]

$$N_c = \left(\frac{Q_u}{c_o}\right) \text{ a } f(\beta, m, \phi) \tag{4}$$

where N_c is the Bearing Capacity Factor. The chosen values of those three dimensionless variables are β = 60°, 90°, 120°,135°, 150°, and 170° to represent a wide range of cone apex angles; m = 1, 2.5, 5,7.5, 10 and ϕ = 0°, 5°, 10°, 15°, 20°, 25°, 30°.

2.1.1 Procedure

The solutions to the problem have been obtained by finite element limit analysis using OPTUM G3 [6]. The mixed bound based numerical computation has been used to obtain a bracketed solution between the lower and upper bound. The model of a conical footing simulated is shown in Fig. 2 (a, b). The symmetry of the problem enables us to perform the analysis by modeling the problem in axisymmetric conditions. The axis of symmetry is situated on the left of the model. The left and right boundaries of the model are restrained to have only vertical displacements. The bottom boundary is restrained in both directions i.e. horizontal as well as vertical. The top boundary is a free surface with no restraints. The footings and soil have a unit weight of zero. The footing has been assigned with rigid material property whereas the soil has been assigned as a Mohr-Coulomb material. In the M-C material modeling, the cohesion has been set to increase with depth and the value of ϕ is fixed. At the top surface of the conical footing, the vertical uniform multiplier load Q_u is applied over the area. The interface between soil and footing is assumed as rough.

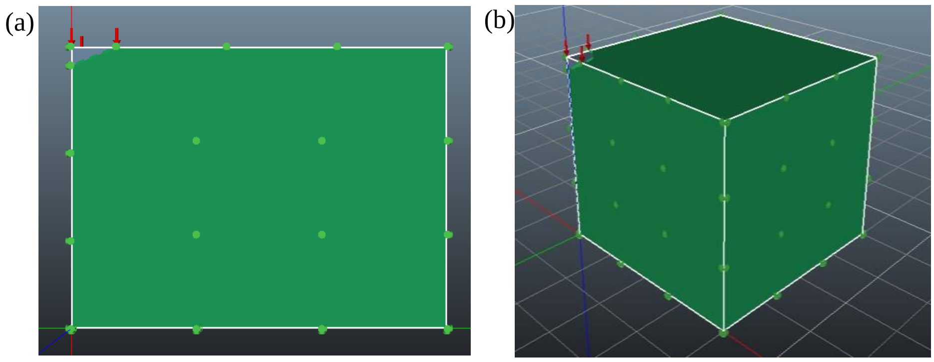

Fig. 2. Stimulation of cone footing model in (a) 2D, (b) 3D view

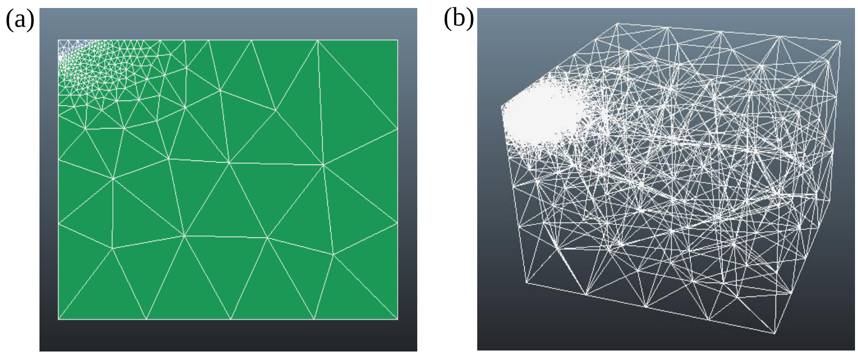

Fig. 3. Mesh used for conical footing model in (a) 2D, and (b) 3D

The domain size is set to be large enough such that the yielding of material remains inside the domain. Automatic mesh adaptivity has been used to refine the mesh in the zone where the yielding of material takes place to avoid extra computational time. In this study, 5 adaptive iterations were used with starting 5000 number of elements and the maximum number of elements was kept at 15,000, consequently, the mesh used can be seen in Fig. 3 (a, b).

3 Results and discussion

All the solutions for Bearing Capacity Factor (N_c) have been obtained with the ranges of β = 60°, 90°, 120°, 135°, 150° to 170°, m = 0-10, and ϕ = 0°–30°. The effects of ϕ, β, and m on the bearing capacity factor N_c are demonstrated in Figures 5, 6, and 7 respectively.

3.1 Verification of the present model study

Before the results and discussion, the results were verified with the results of Suraparb Keawsawasvong [7] and Kumar and Khatri [5]. The study shows N_c is a function of cone apex angle, strength gradient ratio, and anisotropic strength ratio. In the present study, the anisotropic strength ratio was taken as 1.0 making it an isotropic condition but a non-homogenous case with an increase in cohesion with respect to depth. The comparison has been shown in Fig. 4. The AUS model has been used in combination with finite element limit analysis [7] whereas the present study used the Mohr-Coulomb model with mixed bound analysis which is close to the average solutions from UB and LB solutions. Moreover, the results for β = 180° (i.e. a circular footing), m = 0, and c_o = 1 for different values of ϕ has been validated with literature [7]. From Fig. 4 (a, b), it can be observed that the present solution is very much close to the results available in the literature.

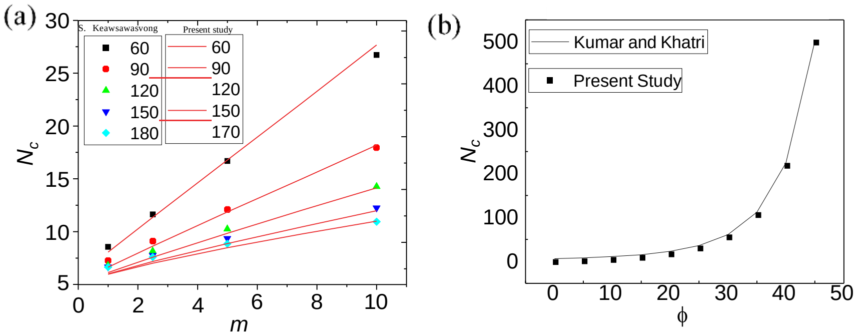

Fig. 4. Validation of N_c values of the present study with results available in the literature (a) Keawsawasvong (2021); (b) Kumar and Khatri (2011)

3.2 Effect of angle of internal friction (ϕ)

The variation of the Bearing Capacity Factor (N_c) with the angle of internal friction of soil (ϕ) for different cone apex angles (β) and cohesion gradient (m) has been presented in Fig. 5. It has been observed that the value of N_c increases with the increase in the ϕ values. The rate of increase in N_c value for higher ϕ and m values.

3.3 Effect of cone apex angle (β)

To examine the effect of the cone apex angle of the footing with respect to the angle of internal friction (ϕ), the results have been obtained for a typical value of m equal to 1 and 10 as shown in Fig. 6(a) and Fig. 6(b) respectively. It can be observed that there is a sharp reduction in N_c value for the case of low apex angle of conical footing. With the increase of apex angle (β), the rate of decrement of N_c value reduces.

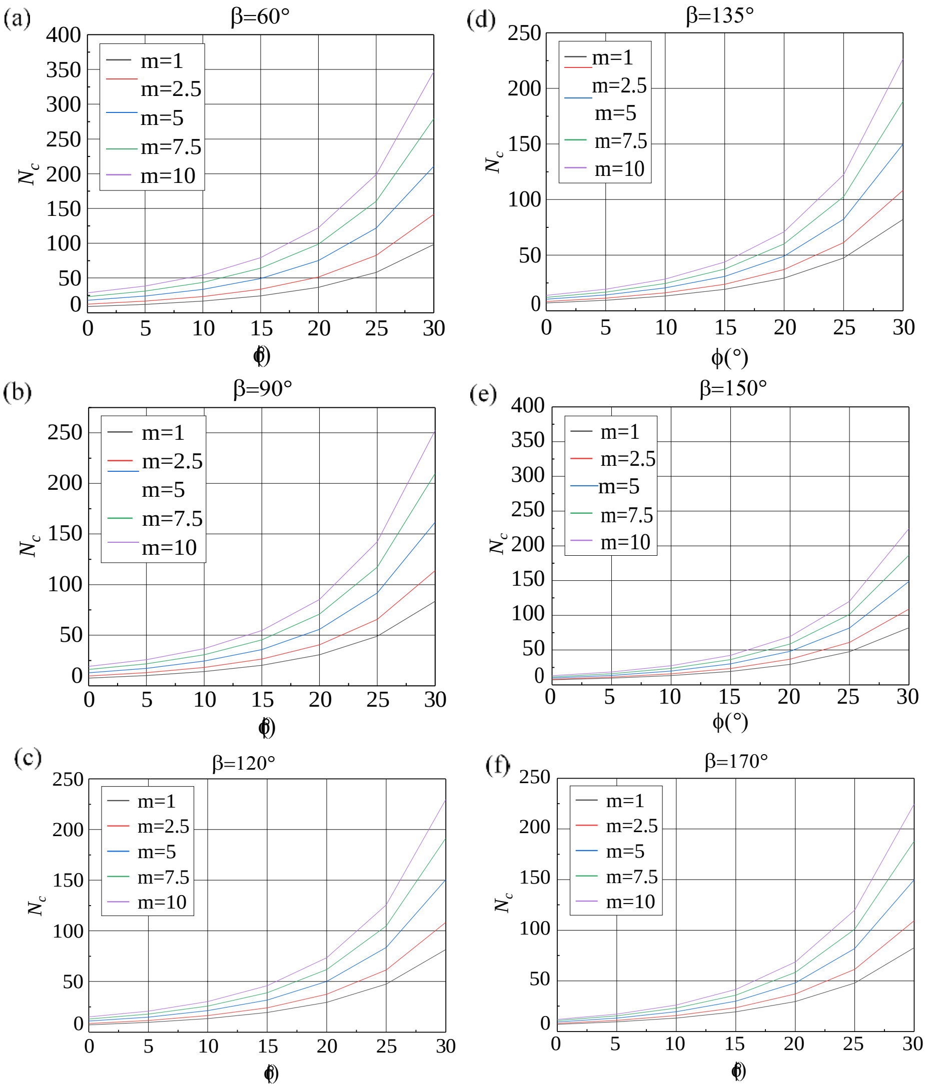

Fig. 5. Variation of N_c with ϕ for m and (a) β = 60°, (b) β = 90°, (c) β = 120°, (d) β = 135°, (e) β = 150°, and (f) β = 170°

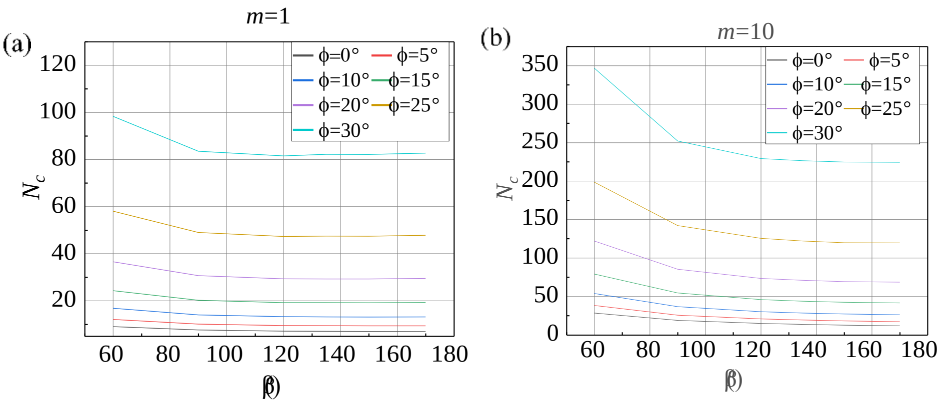

Fig. 6. Variation of N_c with β for (a) m = 1, and (b) m = 10

3.4 Effect of cohesion gradient ratio (*m*)

The variation of the Bearing Capacity Factor (N_c) versus the cohesion gradient ratio (m) can be seen in Fig. 7(a–c) for the cases of ϕ = 0°, 15°, and 30° respectively with β = 60°, 90°, 120°, 135°, 150°, and 170°. It is found that a high m value makes a higher N_c value. The N_c value linearly increases with the increase in m value for any value of β.

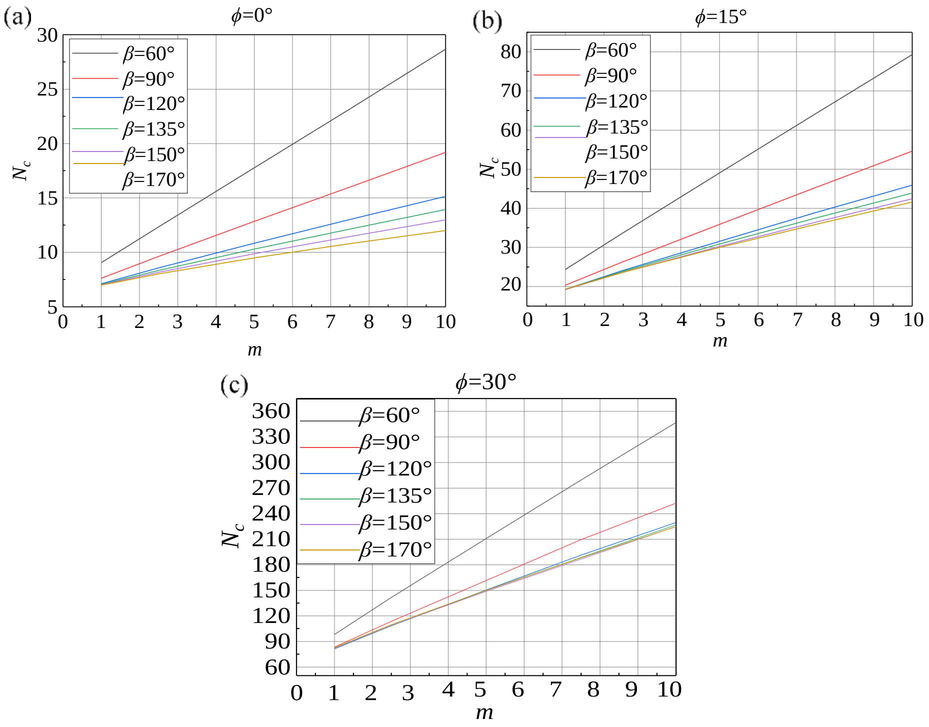

Fig. 7. Variation of N_c with m for (a) ϕ = 0°, (b) ϕ = 15° and (c) ϕ = 30°

4 Conclusions

In the present study, the Bearing Capacity Factor (N_c) of conical footings on clays with linearly increasing cohesion is presented using the mixed bound finite element limit analysis. The magnitude of N_c is significantly dependent on the cohesion gradient ratio (m), cone apex angle (β), and internal friction angle (ϕ). The following conclusions have been made from the present study:

1. The Bearing Capacity Factor (N_c) value increases with the increase in values of internal friction angle (ϕ) and cohesion gradient ratio (m) but decreases with the increase in cone apex angle (β).
2. The rate of increase of N_c value is more for higher values of ϕ and m and less for higher values of β.
3. The mixed bound finite element limit analysis is capable of determining the closer solution for any three-dimensional geotechnical problems.

References

1. Cassidy, M. J., & Houlsby, G. T. (2002). Vertical bearing capacity factors for conical footings on sand. *Géotechnique*, *52*(9), 687-692.
2. Kumar, A., Khatri, V. N., & Gupta, S. K. (2020). Effect of linearly increasing cohesion on the compression and uplift capacity of the under-reamed pile in clay. *SN Applied Sciences*, *2*(2), 1-17.
3. Griffiths, D. V., & Yu, X. (2015). Another look at the stability of slopes with linearly increasing undrained strength. *Géotechnique*, *65*(10), 824-830.
4. Butterfield, R. (1999). Dimensional analysis for geotechnical engineers. *Geotechnique*, *49*(3), 357-366.
5. Kumar, J., & Khatri, V. N. (2011). Bearing capacity factors of circular foundations for a general c–ϕ soil using lower bound finite elements limit analysis. International Journal for Numerical and Analytical Methods in Geomechanics, 35(3), 393-405.

6. Krabbenhoft, K., Lyamin, A., & Krabbenhoft, J. (2020). Optum computational engineering (OptumG3). Available from https://www.optumce.com
7. Keawsawasvong, S. (2021). Bearing capacity of conical footings on clays considering combined effects of anisotropy and non-homogeneity. *Ships and Offshore Structures*, 1-12.