XLIII CILAMCE
21-25, November, 2022
FOZ DO IGUAÇU - PR - BRAZIL

Numerical simulation of bulging and their effects on ultimate bearing capacity in bored piles

Michael Vicente[1], Marko López[2], Jorge Zegarra[2]

[1] *Facultad de Ciencias e Ingeniería, Pontificia Universidad Católica del Perú*
[2] *Área de Geotecnia – Sección Ingeniería Civil, Pontificia Universidad Católica del Perú*
1801 Universitaria Av., 15088, Lima, Peru
michvicente95@gmail.com, malopezb@pucp.edu.pe, jorge.zegarra@pucp.edu.pe

Abstract. Piles are deep foundations that are used to overcoming difficulties of founding on soft soils to ensure structural safety to carry the loads imposed by a structure through a weak soil to a resistant stratum. It is becoming more important to design piles and avoid their shortcomings. Bulging in bored piles is a common event that can occur due to multiple factors. This type of imperfection increases the ultimate bearing capacity of the pile, due to the increase in its geometry, which increases its ultimate shaft resistance. This can be beneficial for the superstructure that said pile supports. However, said increase in the ultimate bearing capacity of the pile must be analyzed cautiously, to avoid overestimations when conducting the structural design of the superstructure. For this reason, a simulation of the ultimate bearing capacity in a concrete pile without a bulging was conducted, in order to compare the results with different cases of piles with bulging, and to calibrate the model.

Keywords: bored piles, ultimate bearing capacity, ultimate shaft resistance.

1 Introduction

Piles are structural elements that are generally used when there is a weak upper soil stratum, so it is necessary to find a layer that is strong enough to withstand the loads transmitted by the superstructure, as stated by Coduto *et al* [1]. Due to their installation, they can be classified as displacement or non-displacement piles. To the latter belong the concrete piles cast in-situ. The behavior of piles in the ideal state has been widely investigated, but it is important to study the behavior of non-ideal conditions on the pile behavior.

Due to the nature of their placement, imperfections are usually present in this type of piles. These may happen, as El-Wakil and Kassim [2] stated, due to various factors such as inadequate ground investigation, natural sources, pile load testing, and construction problems like narrowing, voids, weak areas, and bulging.

2 Model to analyze

The concrete bulging is a widening of the volume of the concrete of the pile on one or all sides, which generates an increase in the section of the pile along said imperfection. To study the effect of concrete bulging on the ultimate bearing capacity in piles, the bearing capacity of an in-situ bored pile (11 m depth and 0.5 m in diameter), placed on a layer of clayey sand and another of rock, was analyzed. The sand layer had a depth of 6 m, and below this was the rock layer. The parameters of the elements identified above are shown in Table 1. It should be considered that the parameters were chosen for the development of this paper. The effect of the concrete bulging was analyzed through the incorporation of a bulging of 2 m depth (almost 20% of the length of the pile) and 0.25 m wide (0.5 m radius), located at depths of 4 m, 5 m, and 6 m (three cases), and the results obtained from the ultimate bearing capacity were compared with those obtained without the presence of said bulging. Also, an interphase was created between both parts, the soil mass (sand-rock) and the concrete pile.

Table 1. Coefficients in constitutive relations

Element	γ [kN/m^3]	γ_{sat} [kN/m^3]	E [kN/m^2]	ν [-]	c' [kN/m^2]	φ' [°]
Pile	25	-	30,000,000	0.2	-	-
Sand	18	20	3,000	0.3	21	30
Rock	24	26	50,000	0.3	42	40

3 Ultimate bearing capacity in a concrete pile without a bulging

3.1 Analytical method (β method)

The β method [3] can be used in cohesive and non-cohesive soils. The ultimate bearing capacity (Q_u) in this method is calculated as follows:

$$Q_u = Q_s + Q_p \tag{1}$$

The ultimate shaft resistance (Q_s) follows the following equation:

$$Q_s = f_s A_s = \beta \sigma'_v \times (perimeter \ \times \ depth) \tag{2}$$

where $\beta = \mu K_0$, as well as $\mu = 2/3 \tan \phi'$, as proposed by Helwany [3]. The coefficient of lateral pressure of the soil at rest was obtained from the Jaky [4] correlation, $K_0 = 1 - \sin \phi'$. Also, σ'_v is the effective vertical stress in the center of the soil layer.
The ultimate point resistance (Q_p) was calculated by means of the following equation:

$$Q_p = f_p A_p = \left[(\sigma'_v)_p N_q + c'_p N_c\right] A_p \tag{3}$$

where $(\sigma'_v)_p$ is the effective vertical stress at the point of the pile, c'_p is the cohesion of the soil under the point of the pile, and N_q and N_c are load capacity coefficients. To calculate them, Janbu [5] proposed the following equations:

$$N_q = \left(tan\, \phi' + \sqrt{1 + tan^2\, \phi'}\right)^2 e^{2\eta\, tan\, \phi'} \tag{4}$$

$$N_c = \left(N_q - 1\right) cot\, \phi' \tag{5}$$

where η is the angle defined in the shape of the cutting surface around the point of the pile, which takes values between $\pi/3$ and 0.58π, as proposed by Wrana [6].
Once the calculations were made, the ultimate shaft resistance was 361.61 kN, while the ultimate point resistance was 1,445.78 kN. This gave an analytical ultimate bearing capacity of 1,807.39 kN.

3.2 Numerical simulation

To corroborate the previously obtained result, a numerical simulation was carried out using the Plaxis software, by means of an axisymmetric model and 15-noded triangular finite elements. The soil under study was described using the Mohr-Coulomb model, with a drained type of drainage, while the pile was described using an elastic linear model, with a non-porous type of drainage. The radius of the soil model was 5 m, while a depth of 9 m for the rock stratum was considered. The parameters considered in the simulation were the same as those mentioned in Table 1.
Loads of 200 kN to 3,200 kN were applied to the modeled pile, which were uphill at a rate of 200 kN per calculated phase. With this, a Load vs. Settlement curve was developed, which is shown in Figure 1 below. As can be seen, the result obtained by means of the numerical simulation was almost the same as that calculated analytically by means of the β method, obtaining an ultimate bearing capacity of approximately 1,800 kN.
The simulation of the ultimate bearing capacity in a concrete pile without a bulging was carried out in order to

compare the results with those of the piles with bulging, and also to calibrate the model to be used.

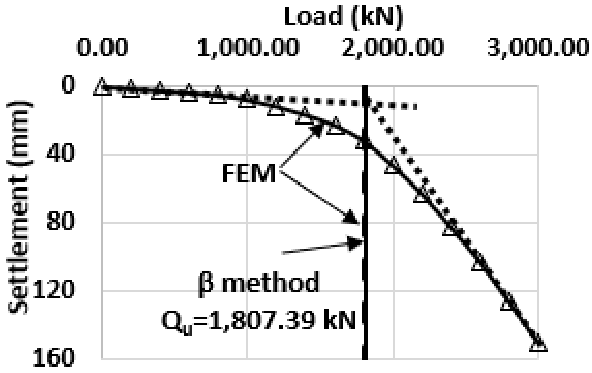

Figure 1. Load vs Settlement curve for a concrete pile without a bulging

4 Ultimate bearing capacity in a concrete pile with a bulging

4.1 Analytical method (β method)

To study the effect of bulging in concrete piles, three cases were analyzed, which are represented in Figure 2, where the bulging is embedded only in the sand (a), between the sand and the rock (b), and embedded only in the rock (c), respectively.

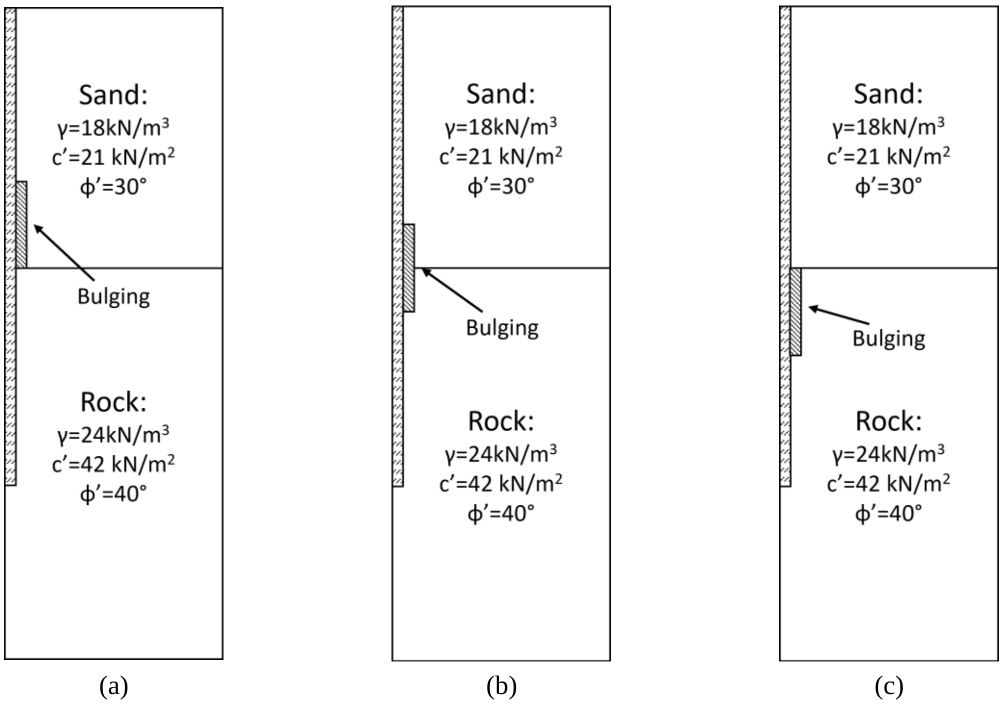

Figure 2. Location of the concrete bulging for depths of: (a) 4 m; (b) 5 m; (c) 6 m.

As can be seen, the ultimate bearing capacity of the pile is modified only in its ultimate shaft resistance. This, because the soil at the point of the pile is not modified. Therefore, the results of the ultimate bearing capacity, for the different cases, were calculated, using eq. (1) to (5) as 1,861.80 kN, 1,874.98 kN and 1,890.25 kN, respectively.

4.2 Numerical simulation

The numerical simulations of the three cases were analyzed. The relationships between the load numerically and the settlement was plotted for concrete piles with bulging to a depth of 4 m, 5 and 6 m. These gave the results shown in Figure 3.

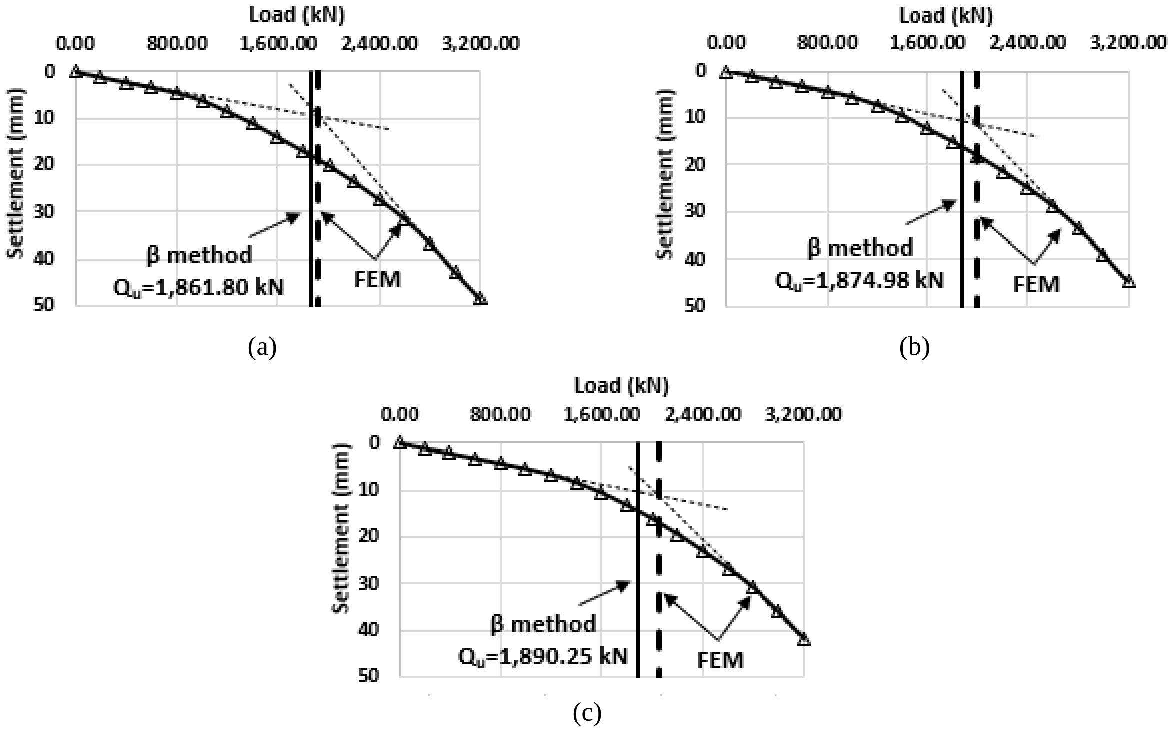

Figure 3. Ultimate bearing capacity obtained for concrete piles with bulging to a depth of: (a) 4 m; (b) 5 m; (c) 6 m.

The quantified numerical results, as well as the comparison between the analytical and numerical results obtained are presented in Table 2.

Table 2. Comparison between analytical and numerical results for the cases studied.

Case	Analytical			Numerical	
	Q_s [kN]	Q_p [kN]	Q_u [kN]	Q_u [kN]	% Var.
No bulging	361.61	1,445.78	1,807.39	1,800.00	-0.41
With bulging (a)	416.02		1,861.80	1,920.00	3.13
With bulging (b)	429.20		1,874.98	1,990.00	6.13
With bulging (c)	444.47		1,890.25	2,050.00	8.45

5 Conclusions

From the results obtained, it can be concluded that the ultimate bearing capacity in concrete piles with bulging, numerically, increases approximately by 4.4%, due to its ultimate shaft resistance due to friction. Although this is beneficial for the superstructure, this higher value must be considered, in order not to overestimate the ultimate bearing capacity in concrete piles cast in-situ, especially in those piles that are considered as "tests". The load-settlement curves have no defined failure load, due to the chosen FEM analysis. Finally, bulging may increase the pile ultimate load though it is still considered as a defect in the pile.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] D.P. Coduto, W.A. Kitch and M.R. Yeung. Foundation Design: Principles and Practices, 3rd Edición.
[2] A. Z. El Wakil and M. Kassim, "Bulging as a pile imperfection". *Alexandria Engineering Journal*, vol. 49, pp. 387-391, 2011.
[3] S. Helwany, "Applied Soil Mechanics with Abaqus". Chapter 8: Piles and pile group. John Wiley & Sons, Inc, 2007.
[4] J. Jaky, "The coefficient of earth pressure at rest". *Journal of the Society of Hungarian Architects and Engineers*, vol. 7, pp. 355–358, 1944.
[5] N. Janbu, "Static bearing capacity of friction piles". *Proceedings of the 6th European Conference on Soil Mechanics and Foundation Engineering*, vol. 1-2, pp. 479-488, 1976.
[6] B. Wrana, "Pile load capacity – Calculation methods". *Studia Geotechnica et Mechanica*, vol. 37, n. 4, pp. 83-93, 2015.