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Soil-pile interaction mechanisms under compressive service load

Mécanismes d'interaction sol-pieu sous charge de service en compression

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ABSTRACT: The evaluation of the response of piles subjected to compressive load is a common geotechnical problem. For non-displacement piles, the contribution of the lateral resistance for the global equilibrium is typically substantial under the service load level. For instance, the lateral resistance can be mobilised for small soil-shaft relative displacements, but the base resistance requires much larger displacements. Due to the pile's shortening and toe displacements, a narrow shear band is formed in the soil surrounding the pile's shaft, which is responsible for most lateral resistance development. In this shear band, shear and volumetric strains of complex evolution occur. However, the induced shear strain will be related to the thickness of the shear band, with the mobilised resistance and with the elastic shortening of the pile and toe displacements. In this work, a simplified model is presented to evaluate the order of magnitude of the shear band strain and its variation in depth, to understand the influence of the shear band thickness and the influence of the axial stiffness of the pile in the mobilisation of the shaft resistance even at very small toe displacements.

RÉSUMÉ: L'évaluation de la réponse des pieux soumis à une charge de compression est un problème géotechnique courant. Pour les pieux sans déplacement, sous le niveau de charge d'utilisation, la contribution de la résistance latérale à l'équilibre global est généralement substantielle. Par exemple, la résistance latérale peut être mobilisée pour de petits déplacements relatifs sol-puits, mais la résistance de base nécessite des déplacements beaucoup plus importants. En raison du raccourcissement du pieu et des déplacements de la pointe, une étroite bande de cisaillement se forme dans le sol entourant la tige du pieu, qui est responsable de la majeure partie du développement de la résistance latérale. Dans cette bande de cisaillement, des déformations de cisaillement et volumétriques d'évolution complexe se produisent. Cependant, la déformation de cisaillement induite sera liée à l'épaisseur de la bande de cisaillement, à la résistance mobilisée et au raccourcissement élastique du pieu et aux déplacements de pointe. Dans ce travail, un modèle simplifié est présenté pour évaluer l'ordre de grandeur de la déformation de la bande de cisaillement et sa variation en profondeur, pour comprendre l'influence de l'épaisseur de la bande de cisaillement et l'influence de la rigidité axiale du pieu dans la mobilisation de la résistance de l'arbre même en cas de très petits déplacements des orteils.

Keywords: Pile; service load; shaft resistance; shear band strain.

1 INTRODUCTION

The bearing capacity of the soil for compression piles is influenced by various factors, such as the nature and conditions of the soil, the presence of water, installation effects, the interface between the pile and the soil, the type of load, time effects, among others, and can be determined as the sum of the mobilised portions at the tip and along the shaft. In piles without the tip activated after installation (common situation in non-displacement piles), the load applied at the top is transferred to the soil through the shaft and progressively to the tip as the lateral resistance from top to bottom is depleted. On the other hand, for many practical situations, the contribution of lateral resistance is dominant for service load levels; that is, it is still far from reaching the ultimate bearing capacity.

This work focuses on the analysis of resistance mobilisation using a simplified model, which assesses the level of shear strain at the soil-pile lateral interface and its relationship with the mobilised resistance and the elastic shortening of the pile. Various scenarios are analysed, with piles of different lengths and diameters, where the tip contribution is 20% of the load applied at the top. Finally, a critical review of the values obtained for elastic shortening is discussed.

2 DESCRIPTION OF THE SIMPLIFIED MODEL

The total resistance (R_t) of a compression pile is given by the sum of two components: lateral resistance (R_s) and base resistance (R_b). The involved resistances are calculated as follows:

$$R_t = R_b + R_s - W \tag{1}$$

$$R_b = A_b\, q_b \tag{2}$$

$$R_s = A_s\, q_s \tag{3}$$

where W is the weight of the pile (often neglected due to its magnitude compared to other forces involved), A_b is the base area of the pile, q_b is the unit base resistance, A_s is the shaft area, and q_s is the unit lateral resistance.

Defining the parameter β as the ratio of q_s to σ'_{v0} (initial effective vertical stress of the soil), the accumulated lateral resistance (R_s) from the surface (z=0) to a depth of $z=L$ is calculated as:

$$R_s = \int_0^L P_s\, q_s\, dz = \int_0^L P_s\, \beta\, \sigma'_{v0} dz \tag{4}$$

where P_s corresponds to the perimeter of the pile at depth z. Usually, constant values for β are adopted with depth. Assuming a constant value neglects the effect of soil dilatancy. In practice, this is not observed since β has a maximum value at the surface, decreasing with depth. The superficial soil tends to be over-consolidated, dilating before reaching the critical state under shearing. Under confined conditions, the increase in soil volume results in increased average stresses and, consequently, increased normal stress around the pile. As granular soil is a material with frictional resistance, the increase in normal stress causes an increase in the lateral resistance of the pile. In more considerable depth, the soil is typically normally consolidated to slightly over-consolidated. Distortional deformations cause small soil contraction deformations, and the unit resistance tends towards a particular value, often represented by $\sin\phi'_{cs}$, where ϕ'_{cs} is the angle of shear resistance at the critical state (Lourenço, 2020). Based on load test records on piles compiled by Fellenius (2019), this model adopts the following form for the function $\beta(z)$:

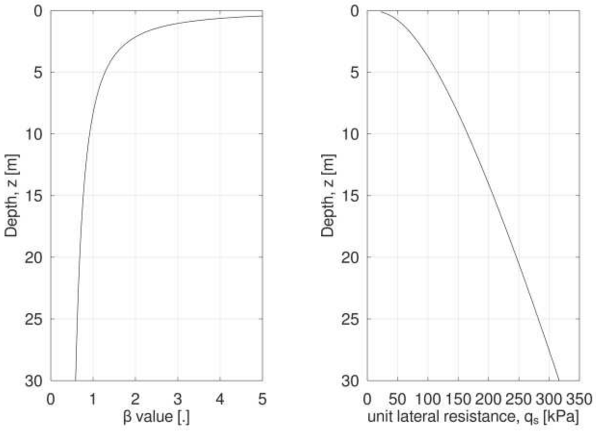
$$\beta(z) = a\, z^b + c \tag{5}$$

where a, b, and c are constants. Lourenço & Santos (2021), fitting equation (5) to the results of Fellenius (2019), yields values of a=2.8184, b=−0.6249, and c=0.25. Note that this type of function allows for a curve with a horizontal asymptote for z=0 and a vertical asymptote for z=+∞ with a value of 0.25. This value corresponds physically to $k_0 \times \sin\phi'$ (i.e. 0.5×sin30°).

Since, as defined earlier, $\beta = q_s/\sigma'_{v0}$, adopting a constant value for the soil unit weight yields the evolution of the unit lateral resistance with depth:

$$q_s(z) = \left(a\, z^b + c\right) \gamma\, z \tag{6}$$

Figure 1 presents the evolution of the $\beta(z)$ and $q_s(z)$, determined by equations (5) and (6). For these curves, a unit weight value of 18 kN/m^3 was assumed.



a) β value *b) unit lateral resistance (q_s)*

Figure 1. Evolution of the β and unit lateral resistance with depth

Knowing the load that the structure transfers to the top of the pile (Q_T), which is balanced by the lateral and tip resistance of the pile ($Q_T = R_s + R_b$), it is possible to know the axial force along the pile. For this, it is necessary to integrate equation (6) from the surface to the desired depth, resulting in the following equation:

$$\begin{aligned} N(z) &= Q_T - \int_0^z \pi D\, q_s(z)\, dz \\ &= Q_T - \pi D \left(\frac{a\, \gamma\, z^{(b+2)}}{b+2} + \frac{c\, \gamma\, z^2}{2} \right) \end{aligned} \tag{7}$$

where πD corresponds to the perimeter of the pile (assuming the pile has cylindrical geometry). Finally, the evolution of elastic shortening with depth ($\rho(z)$) is obtained through the depth integration of (7) divided by the axial stiffness modulus (EA):

$$\begin{aligned} \rho(z) &= \int_0^z \frac{N(z)}{EA}\, dz \\ &= \frac{1}{EA} \left(Q_T\, z - \pi\, D \left(\frac{a\, \gamma\, z^{(b+3)}}{(b+2)(b+3)} + \frac{c\, \gamma\, z^3}{6} \right) \right) \end{aligned} \tag{8}$$

The above equation allows determining the total elastic shortening (ρ_L), corresponding to the value of elastic shortening calculated at the base of the pile. This value will estimate the shear strain imposed on the shear band generated along the lateral interface. The thickness of this shear band is difficult to predict because: i) it is not an intrinsic characteristic of either the soil or the interface, also depending on the boundary conditions of the problem; ii) the thickness of the shear band tends to decrease with decreasing soil compactness; iii) the thickness of the shear band increases with the roughness of the pile-soil interface.

However, Fioravante (2002) sought to systematise the issue for pile cases, proposing that the interface thickness be about 2 to 5 times D_{50} for piles with a smooth interface and 10 to 15 times D_{50} for piles with a rough interface (where D_{50} corresponds to the average effective diameter of the soil particles).

To estimate the shear band's shear strain, it is assumed that the pile moves due to elastic shortening and the surrounding soil remains fixed, i.e., the relative displacement (d_{rel}) can be determined by the difference between the total elastic shortening of the pile and the elastic shortening at a depth determined through (8), as indicated in the following equation:

$$d_{rel}(z) = \rho_L - \rho(z) \qquad (9)$$

Therefore, all soil deformation is concentrated in the shear band, and the shear strain (γ) in each point is given by the relative interface displacement determined through (9) divided by the shear band thickness (t_{intf}), as indicated by the following expression:

$$\gamma(z) = \frac{d_{rel}(z)}{t_{intf}} \qquad (10)$$

Considering cast-in-place piles installed in sands, it is assumed that the effective diameter of the soil (D_{50}) will vary between 0.1 and 1 mm, generating shear bands with thicknesses of 1 to 15 mm. From the analysis of a series of interface test results compiled by Lourenço (2020), the mobilisation of maximum resistance is obtained from a shear strain level ranging from about 100% to 200%.

3 MODEL FOR PILES UNDER LOW-SERVICE LOAD

A model was developed for typical service conditions, where the applied load is resisted mostly by lateral resistance. For the development of the model, the following assumptions were adopted:

- the pile is cylindrical, with a diameter (D) ranging from 0.30 to 2.00 m;
- the ratio Length/Diameter (L/D) ranges from 5 to 50, which correspond from very short to very long piles;
- the pile is made of reinforced concrete (E = 30 GPa);
- the soil has a constant unit weight of 18 kN/m^3 without water-table;
- two types of soils are analysed: a fine sand, with a D_{50} of 0.1 mm, and a medium sand, with D_{50} of 1 mm; it is assumed that the shear band for these cases will have a thickness of 1 mm and 10 mm, for fine sand and medium sand respectively;
- the lateral resistance of the pile corresponds to 80% of the total resistance (i.e., the base resistance accounts for 20% of the total resistance);
- the tip of the pile lies on a very stiff soil, and it has no displacements.

The results of this parametric calculation are presented in Figure 2. From the analysis of the figure, it can be observed that:

i) in all cases, it is assumed that the lateral resistance is fully mobilized. From equation (6), it is possible to determine the relationship between the lateral resistance (R_s) and the length (L) of the pile, expressed through the following equation (Lourenço & Santos, 2021) presented in Figure 2a:

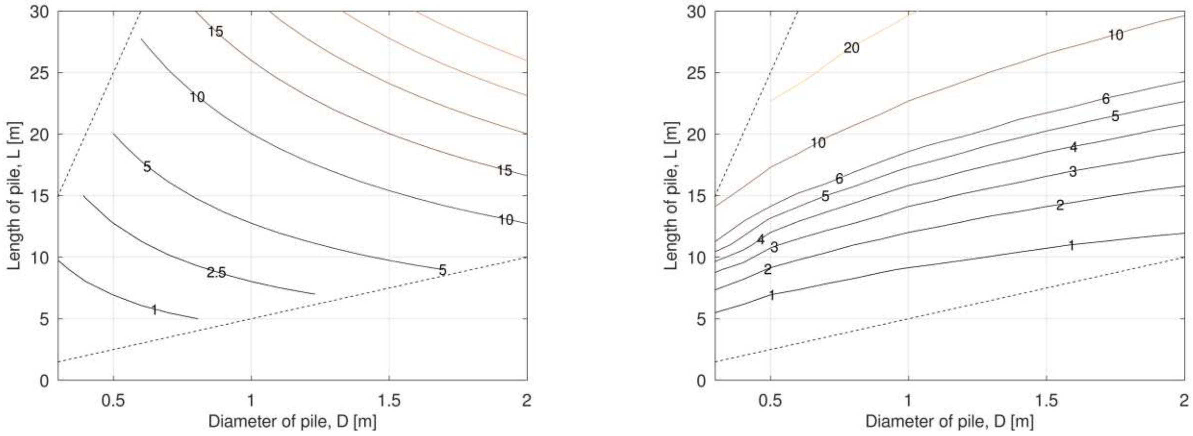
$$R_s[kN] = D\gamma(6.44L^{1.3751} + 0.393L^2) \qquad (11)$$

ii) lateral resistance (R_s) is directly proportional to the diameter (D) and varies with the length of the pile (L) raised to the exponent of 1.38 to 2. Values between approximately 1 and 30 MN of lateral resistance were obtained (Figure 2a).

iii) the total elastic shortening is inversely proportional to the pile's diameter and modulus of elasticity. From equation (8), it is possible to determine the relationship:

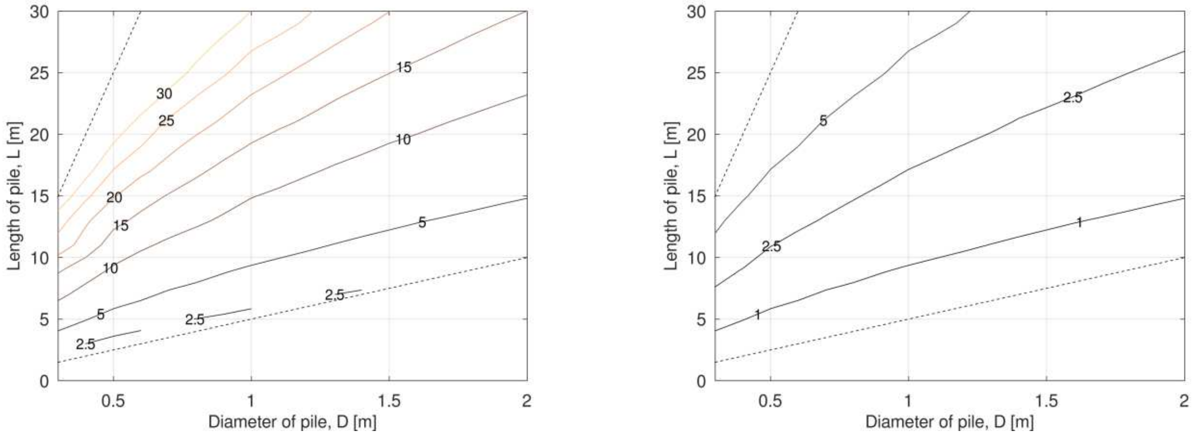
$$\rho[mm] = \frac{L^{2.375}}{245.2D} + \frac{L^3}{3635.8D} \qquad (12)$$

iv) It varies with the pile length raised to the exponent comprised between 2.38 and 3; in other words, the value of the shortening is mainly conditioned by the length of the pile (Figure 2b); for example, a pile with a length of 20 m and a diameter of 0.5 m has approximately the same lateral resistance as a pile with a length of 10 m and a diameter of 1.5 m; however, the elastic shortening of the former is about 15 mm, and the latter is 1 mm.



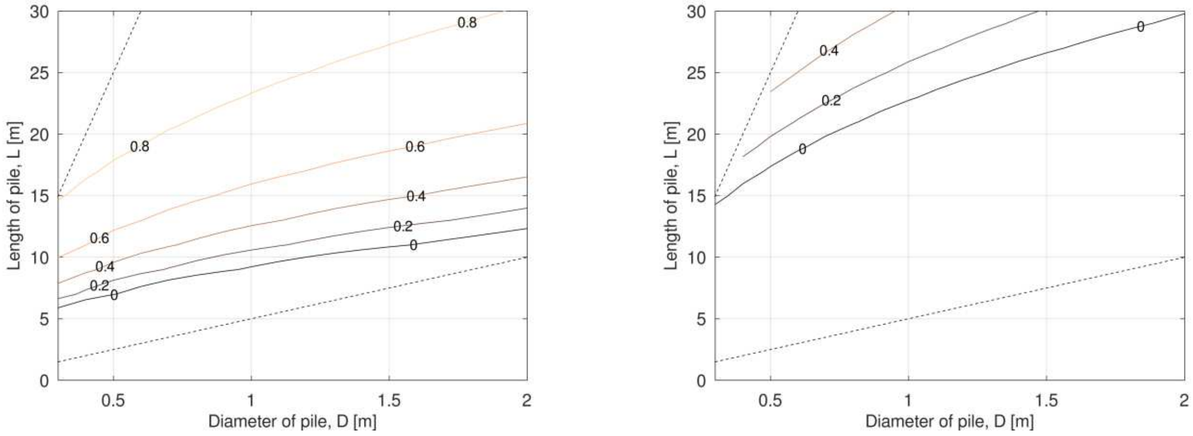
a) lateral resistance (MN)

b) total elastic shortening, ρ_L (mm)



c) top pile axial stress (MPa)

d) tip pile axial stress (MPa)



e) ratio of the shaft area where interface shear strain is greater than 1, for the pile installed in fine sand (t_{inf}=1 mm)

f) ratio of the shaft where interface shear strain is greater than to 1, for the pile installed in medium sand (t_{inf}=10 mm)

Figure 2. Parametric study results.

v) elastic shortening is very small, typically on the order of millimeters; in slender piles, shortening may reach 2 cm (Figure 2b);vi) the maximum base stress at the tip of the pile is usually smaller than 5 MPa (Figure 2d);

vii) for piles installed in fine sand, the ratio of the shaft where interface shear strain is greater than 1 is considerable; for example, if $L>5.9D+8.2$, more than top 60% of pile has the lateral resistance fully mobilized (Figure 2e); for short piles, the values presented in Figure 2e are merely indicative, as the influence of the tip should be greater than assumed;

viii) for piles installed in medium sand, the ratio of the shaft where interface shear strain due to elastic shortening allows some lateral resistance is considerable; for exasmple, if $L<8.8D+12.4$, no lateral resistance occurs (Figure 2e);

ix) if tip settlement occurs in the pile installed in fine sand, all interface is fully mobilized for a tip settlement of 1 mm;

x) from Figure 2f, it can be inferred that for mobilizing the lateral resistance in medium sand, the tip settlement should be around 1 cm, which can be quite high, when considering the pile tip axial stress due to service loads. So, the full mobilization of the lateral resistance may not occur in all cases.

4 CONCLUSIONS

This article discussed the application of the beta method in assessing the strain level of the shear band mobilised for lateral resistance. It was observed that the mobilisation of lateral resistance corresponds to maximum relative displacements of a few millimetres. However, these displacements are sufficient to mobilise the entire resistance, as the strains resulting from the adopted model are typically over 100%.

As discussed in this article, the capacity for lateral resistance to be fully mobilised with elastic shortening will depend on the shear strain imposed on the shear band, which will have a thickness depending on the soil's particle size. The shear band will be a few millimetres thick for fine to medium sands. For coarser soils, where the shear band thickness is in order of centimetres, elastic shortening will not be sufficient to deplete the ultimate lateral resistance.

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