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Application of reliability-based design to piles in the collapsible Argentinean loess

Application de dessin basé en confiance des pieus en les loess pliant de Argentine

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ABSTRACT
Cast-in-place piles are the most commonly foundation type used in Cordoba city, Argentina. Foundation of buildings usually consists in concrete piles embedded in collapsible loess with the pile tip in contact with a lower and stiffer stratum, typically sand or cemented silt. Piles in loess are frequently designed using safety factor criteria for both, short- and long-term behavior. Usually, there is no information about the reliability of piles since safety factors do not provide information on failure probability. A reliability analysis is implemented in this work to predict the behavior of piles in the Argentinean loess. Reliability-based technique is used to compute the failure probability of piles for long- and short-term performance. Pile capacity is computed by theoretical formulations using classical bearing capacity factors. The skin resistance is estimated by the α method. Results show that failure probability for a short-term analysis is smaller than for long-term analysis. Also, failure probability increases as safety factor decreases. Finally, in order to obtain a given failure probability the safety factor to be considered depends on the pile type.

RÉSUMÉ
Les pieus perforés à main sont type de fondation le plus communément utilisé a Cordoba ville (Argentine). La fondation de bâtiments s'agit des pieus du béton enfoncés en loess pliant avec la pointe en contact avec un strate inférieur plus raide généralement sable ou boue cimenté. Les pieu en loess sont frécuemment dessinés en utilisant critères du facteur de sécurité. D'habitude il n'y a pas d'information sur la possibilité de l'échec. Une analyse de confiance est implémenté dans ce travail pour prédise le comportement des pieus dans les loess du Argentine. On s'utilise la technique sur la base du confiance pour calculer la probabilité de l'échec des pieus pour le long terme et court terme. La capacité du charge est calculée par formulations théoriques en utilisant les facteurs de capacité de charge classiques. La résistance latéral est estimée par le méthode α. Les résultats montre que la probabilité de l'échec pour l'analyse en court terme est plus petite qu'a long terme. En plus, la probabilité de l'échec augmente quand le facteur de sécurité diminue. Finalement, pour obtenir une probabilité déterminé d' l'échec, le facteur de sécurité à considéré ça dépend du type dus pieus.

1 INTRODUCTION

Loess deposits cover 600.000 Km^2 all around Argentina (Bloom, 1992). Argentinean loess has mechanical properties highly dependent on moisture content. Loess collapses when water content increases. As consequence, the soil compressibility increases and the undrained shear strength decreases. Also consolidation and downward movement of the soil surrounding the pile generate negative skin friction. Soil collapse modifies pile behavior. At low moisture content Argentinean loess develops high stiffness and apparent cohesion. In this situation, the contribution of side resistance prevails in the ultimate pile capacity. On the other hand, when soil saturates it behaves as a very soft soil; and apparent cohesion disappears. In this case, vertical loads are transmitted from the shaft to pile tip. This load transfer mechanism depends on the unsaturated and saturated loess mechanical properties (Redolfi, 1993).

Foundation of buildings in Cordoba City usually consists in concrete piles embedded in collapsible loess with the pile tip in contact with a lower and stiffer stratum. Piles function as a combination of friction resistance and end bearing. Friction or end bearing prevail depending on soil properties (Bowles, 1988). At natural moisture content, short-term calculation better represents pile behavior. After soil saturates, the proper analysis requires long-term calculations.

The purpose of this study is to show that reliability analyses are useful to rationally design piles in collapsible soils. Uncertainties and variability of soil mechanical properties as well as doubts in load conditions may easily be considered in this type of analysis (Harr, 1987). Resistant parameters of loess from the central part of Argentina are highly variable (coefficient of variation COV higher than expected). Spatial variability as well as presence of precipitated salts and carbonate nodules may be responsible of the observed dispersion. This high COV contributes to enhance the failure probability of piles in loess.

The use of mean values for the soil properties in geotechnical engineering is being replaced by reliability based analysis (O'Neill, 1986; Ahammed and Merches, 1997; Tandjiria et al., 2000; Al-Homoud and Tahtamoni, 2000; Griffiths and Fenton, 2004; Christian, 2004; Zhang, 2004). This method predicts failure probability by considering the variability of soil parameters.

2 BEHAVIOR OF PILES IN LOESS

Dip foundations design, considers soil-pile interaction (Prakash and Sharma 1990). The U.S. Army Corps of Engineers (US-ARMY, 1991) design method computes allowable and ultimate bearing capacity and settlement by using safety factors. Suggested safety factors depend on the available data and knowledge about pile behavior and soil properties (Fig. 1).

In all cases, soil properties are considered as deterministic values, without exploring the probabilistic deviations and spatial variability. Pile bearing capacity depends on the skin [Q_s] and tip capacity [Q_t] as:

$$Q_{ult} = Q_s + Q_t \tag{1}$$

$$Q_s = \left[K \cdot \gamma \cdot H \cdot tg(\delta) + \alpha \cdot c\right] \cdot A_s \tag{2}$$

$$Q_t = \left[\gamma H \cdot N_q\right] \cdot A_t \tag{3}$$

Where A_s = friction area of the pile, K = coefficient of lateral pressure, α=constant that depends on the soil undrained strength, H =pile length, δ=friction angle between the soil and the pile, γ' = effective unit weight, A_t = tip area, N_q = Terzaghi´s bearing capacity factor.

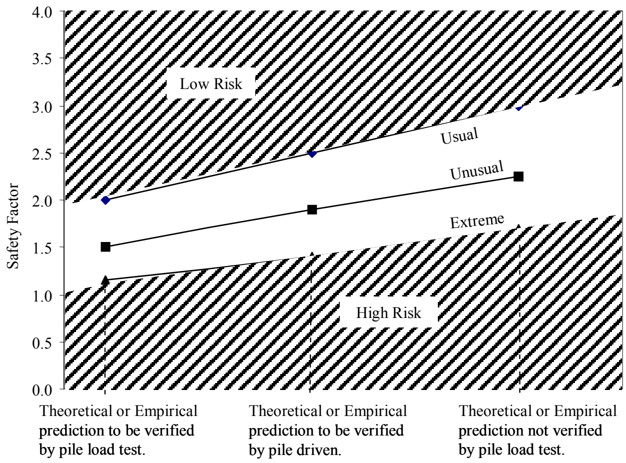

Figure 1: Suggested minimum safety factors for compressed piles (data from US-ARMY, 1991)

On the other hand, performance of piles also depends on pile settlements. There are many alternatives to compute pile settlements: a) empirical formulations, b) closed form solutions, c) elastic analysis, d) finite element method, etc.

Vesic (1977) computes pile settlements [A_T] as the contribution of the elastic deformation of the pile [A_E], settlements related to the load transfer from the pile tip to soil [A_P] and settlements related to the load transfer from the pile shaft to the lateral soil [A_F] (US ARMY, 1991):

$$A_T = A_E + A_P + A_F \tag{4}$$

Redolfi (1993) developed an alternative method based on theoretical load transfer functions. This method can be use to consider the effect of soil saturation along the pile shaft and the corresponding load transfer from the shaft to the pile tip. This method is very useful to consider behavior of piles in partially saturated loess.

3 RELIABILITY THEORY: UNDERLYING CONCEPTS

Safety factors used for the calculation of pile foundations are defined as the ratio of capacity C to demand D.

$$FS = \frac{C}{D} \tag{5}$$

Equation (5) suggests that both capacity and demand are deterministic values having 100% of occurrence probability. However, in most cases both capacity and demand are not unique values, since they depend on soil properties, environment condition, constructive processes, etc. Hence, capacity and demand have some variability that can be taken into account by means of probabilistic analysis. In this case, C and D are characterized by a probability distribution function (e.g. mean and standard deviation for normally distributed parameters). The intersection between the C and D functions gives the probability that the safety factor being lower than 1 (demand exceeds capacity - Fig. 2). Similar analysis can be made if capacity shows some probability distribution and demand is assumed to be deterministic. The difference between the capacity and demand functions define the safety margin (S),

$$S = C - D \tag{6}$$

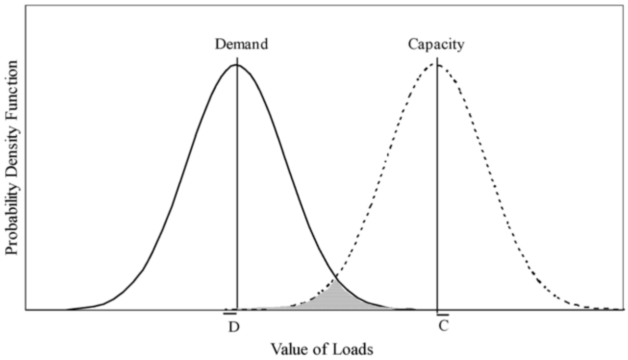

Figure 2: Probabilistic description of safety factor.

Parameter S is also a probabilistic variable with negative and positive values. Negative values of S indicate that demand exceeds capacity. The number of standard deviations $\sigma_{[S]}$ giving null S is known as reliability index (β), and it can be computed as:

$$\beta = \frac{\overline{C} - \overline{D}}{\sqrt{\sigma^2_{[C]} + \sigma^2_{[D]} - 2 \cdot \rho \cdot \sigma^2_{[C]} \cdot \sigma^2_{[D]}}} \tag{11}$$

Where $\overline{C}$ and $\overline{D}$ are the mean values of capacity and demand, $\sigma_{[C]}$ and $\sigma_{[D]}$ are the standard deviation of capacity and demand and ρ is the correlation coefficient. This last parameter indicate how two variables are related each other. Its value falls between 1 for directly related variables and -1 for inversely related variables:

$$\rho_{x,y} = \frac{\frac{1}{N}\sum_{i=1}^{N}\left[x_i - E_{[x]}\right]\left[y_i - E_{[y]}\right]}{\sigma_{[x]} + \sigma_{[y]}} \tag{12}$$

Where N is the number of data, x_i and y_i are i values of each variable, E represent expected values and σ is the standard deviation. The probability of failure $p_{(f)}$ is computed from the β value and the probabilistic distribution function. For normally distributed variables failure probability yields:

$$p_{(f)} = \frac{1}{2} - \frac{1}{\sqrt{2 \cdot \pi}} \cdot \int_0^{\beta} e^{\left[-\frac{x^2}{2}\right]} dx \tag{13}$$

From the preceding procedure it is possible to obtain expected values and COV for capacity and demand, the failure probability and the reliability of the system.

4 PROBABILISTIC ANALYSIS OF PILE BEHAVIOR

Reliability based-analysis is applied to piles in loess. Two cases are analyzed: (a) floating piles and (b) end-bearing piles. (Fig. 3)

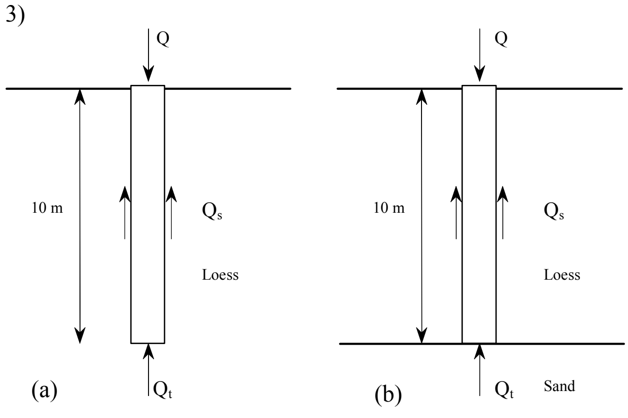

Figure 3: (a) Floating pile, (b) End-bearing pile

The main mechanical and physical properties of loess are shown in Table 1. Finally, the considered external load is Q = 700 kN.

For most real cases, piles are set in partially saturated loess (at natural moisture content). In this case, short-term analysis based on total stresses is more representative of real behavior; even this is not a conservative design. On the other hand, after soil saturates, apparent cohesion vanish (Table 1) and long-term design based on effective parameters better predict pile behavior.

Table 1: Relevant physical and mechanical properties of soils (data from Moll and Rocca 1991 and Francisca et al. 2002).

	Loess		Sand
	Long term	Short term	Long term
γ_d [kN/m^3]	12.81	12.81	16.00
ω_{HN} [%]	14	14	8
e	0.91	0.91	0.60
c [kN/m^2]	0 (1)	30 (2)	0
σ_c [kN/m^2]	0	5	0
ϕ [°]	28 (1)	20 (2)	33
σ_ϕ [°]	3	3	2.8*

Note: γ_d = dry unit weight, ω_{HN} = moisture content, e = void ratio, c = cohesion, σ_c = standard deviation of cohesion, ϕ = friction angle and σ_ϕ = standard deviation of friction angle.* Computed form the mean value and the coefficient of variation reported by Harr (1987), (1) data from consolidated drained triaxial test, (2) data from consolidated undrained triaxial tests performed at natural moisture content (total stresses analysis).

4.1 *Deterministic Results: Expected Values*

Table 2 shows the expected values of bearing capacity obtained by the method suggested by US ARMY (1991). In both cases, short-term bearing capacity exceeds long-term resistance. Obtained frictional contribution surpasses the applied load (700 kN) for short-term behavior. In this case, no load is transferred to the pile tip. Observe that when loess saturates, its mechanical properties changes (Table 1). Skin capacity decreases and load is transferred to deeper sections and finally to the pile tip (Redolfi, 1993).

Table 2: Expected values of bearing capacity and safety factors.

Condition	Floating Pile		End-bearing Pile	
	Long term	Short term	Long term	Short term
Q_s [kN]	454	1422	454	1422
Q_t [kN]	568	470	1007	1915
Q_{ult} [kN]	1022	1892	1461	3337
SF [for Q = 700 kN]	1.46	2.70	2.08	4.76

Table 3 shows the expected values of settlements using Vesic´s method (Vesic 1977) and Redolfi´s method (Redolfi 1993). There is a good correlation between the settlements computed by the two methods. Redolfi´s method gives lower values for the four cases analyzed. Elastic deformations are negligible. For short-term analysis, settlements related with the load transfer from the pile tip to soil [A_P] are null since all external loads are supported by the pile shaft. To fully develop lateral resistance, settlements should be close to 0.5 to 1.0 cm.

Table 3: Expected values of pile settlement.

Settlements	Floating Pile		End-bearing Pile	
	Long term	Short term	Long term	Short term
A_E [cm]	0.04	0.03	0.04	0.03
A_P [cm]	2.70	0.00	1.28	0.00
A_F [cm]	0.60	0.27	0.33	0.27
A_T [cm] (s/ Vesic, 1977)	3.30	0.30	1.65	0.30
A_T [cm] (s/ Redolfi, 1993)	2.00	0.14	1.60	0.20

4.2 *Reliability Based Design*

Two random variables are considered: friction angle and cohesion. Bearing capacity and settlements were computed considering the mean and standard deviation of both parameters, following the procedure presented earlier. Mean values and standard deviation of bearing capacity and settlements of piles are obtained.

Failure probability is determined by assuming a normal distribution function for the soil properties (making sure that no negative values without physical meaning are generated). The normal distribution was selected since this is the best probabilistic function that can be used when only the mean and standard deviation of the physical parameters are known (Harr, 1989).

Fig. 4 shows the probability distribution computed for the bearing capacity. Short-term bearing capacity resulted higher than long-term bearing capacity for end-bearing and floating piles. In addition, end-bearing piles have higher capacity than floating piles for short- and long-term behavior respectively.

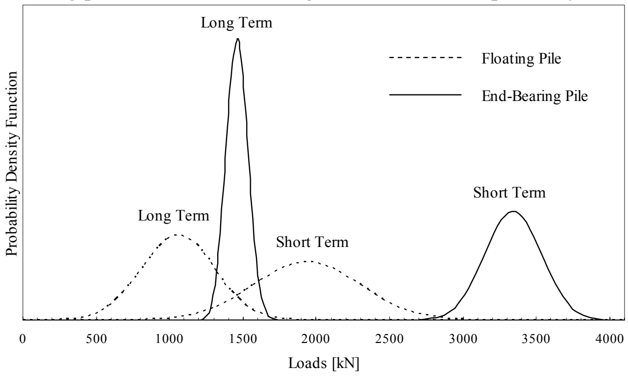

Figure 4: Computed bearing capacity distribution

From Fig. 4 and assuming several values for the demand it is possible to establish a relationship between the failure probability and safety factor as shown in Fig. 5. Obtained results suggest that in order to obtain the same failure probability, the safety factor that geotechnical engineers should use for the design of floating piles is almost 2.5 times the safety factor used for tip piles even thought most of design codes or manuals do not consider the pile type (Fig. 1, US-ARMY 1991). As Fig. 5 is plotted in semi log scale there is a critical safety factor value for which the failure probability remains almost constant for most of practical considerations.

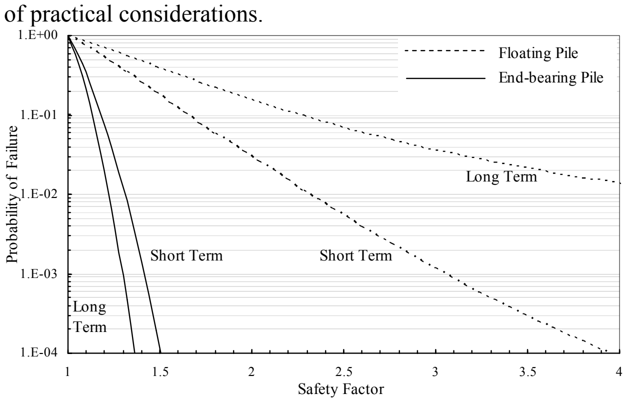

Figure 5: Probability of failure versus factor of safety

Similar analysis can be performed in order to compute pile settlements. Fig. 6 shows the probability that settlements overpass 0.02 m for piles of 0.8 m in diameter and 10.0 m in length for different live load. For a given demanding load, the probability that settlements exceed 0.02 m is higher for floating piles than for the end-bearing piles, for both short-term and long-term behavior. Additionally, the probability that settlements exceed 0.02 m is higher for the long-term than for the short-term response. Notice that short-term and long-term behaviors were assumed as representative of piles in unsaturated and saturated loess respectively. Even soil saturation is not considered in this work, from the same Fig. 6 it can be observed that when moisture content modifies, the corresponding curve of pile behavior also changes resulting in a very important increase of the probability that settlements surpass 0.02 m.

The same Fig. 6 presents the corresponding simulated load-settlements response which shows a bilinear behavior for the four cases considered in this work. For low loads, the load-settlement curves for end-bearing- and floating-piles are almost coincident. For loads that exceed the frictional capacity, both curves separate because of the different resistant of the soil at the pile tip. Floating piles shows higher settlements than end-bearing piles after the frictional capacity is exceeded.

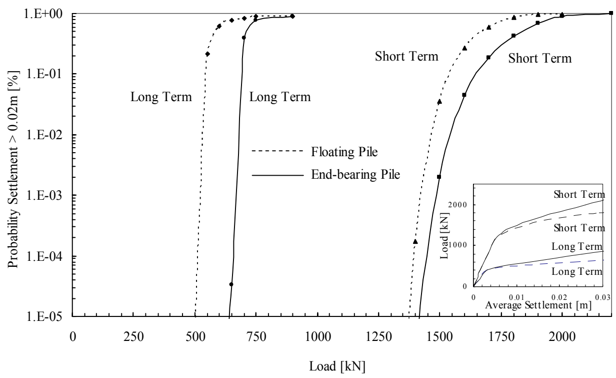

Figure 6: Influence of the demanding loads on the probability that long- and short-term settlements overpass 0.02 m for floating- and end-bearing piles 0.8 m in diameter and 10 m in length.

Fig. 7 shows a design chart to compute the probability that piles 10 meters in length overpass 0.02 m of settlements. The corresponding simulated load settlements response is also shown in the same figure. For a given external load, the higher the pile diameter the lower the probability that settlements exceeds 0.02 meters. Additionally, behavior of both floating and end-bearing piles are almost identical for small piles diameters since the tip pile contribution is very small. As the pile diameter increases, end bearing piles show an evident lower probability that settlements exceed admissible values.

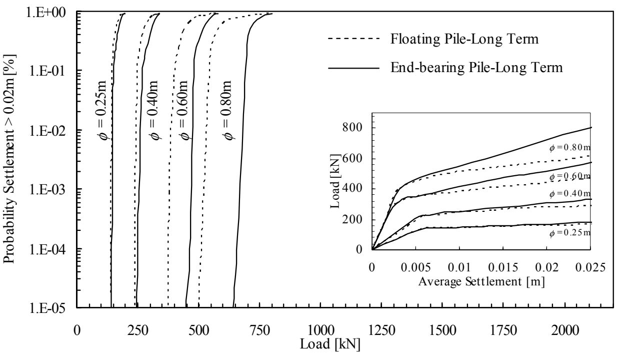

Figure 7: Influence of the demanding loads on the probability that long-term settlements overpass 0.02 m for end-bearing-and floating- piles of several diameter and 10 m in length.

5 CONCLUSIONS

Reliability based analysis was applied to pile in loess. The main conclusions of this research can be summarized as follow:

- Reliability analysis allows geotechnical engineers to better understand the behavior of piles in loess. Very small additional information is needed, as for example the mean and standard deviation of soil parameters, to obtain valuable information on the performance and reliability of the foundation under design.
- The safety factor by itself do not gives information about how far is the failure and how reliable is the pile.
- For the piles considered in this work, the safety factor to be used for the design of floating piles should be almost 2.5 times the usual value used for tip piles.
- A critical value of safety factor was identified in this work for which the failure probability remains almost constant for most practical considerations.
- For a given vertical load, floating piles have higher probability that settlements exceed 0.02 m than end bearing piles for both the short-term and the long-term response. Also, the probability that settlements exceed 0.02 m is higher for long-term than for short-term pile behavior.

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