Improved Safety Assessment of Pile Foundations Using Field Control Methods

Évaluation améliorée de la sécurité des fondations sur pieux à l'aide de méthodes de contrôle in situ

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ABSTRACT: The theme of foundation safety has historically deserved special attention in both theory and practice due to the need to find optimized solutions which balance cost and safety. Safety against bearing capacity failures (ultimate limit states) continues to be a key topic, particularly in pile foundations, as opposed to other foundation types in which serviceability limit states tend to dominate safety considerations. The paper presents a new approach, in which Bayesian inference is used to combine bearing capacity predictions and field controls, so as to improve reliability assessment and, possibly, lead to more economic design. For bearing capacity predictions semi-empirical procedures based on SPT blow-count are frequently used, and those are the ones addressed in the paper. Rebound and set obtained during pile driving are generally used for uniformity control only, but the paper explores the possibility of combining this duly interpreted information with the design predictions, so as to achieve more economical foundations, while maintaining the prescribed level of safety against failure. The extension of the approach to the case where pile load tests (both static and dynamic) are also available is straightforward and discussed in referenced papers.

RÉSUMÉ : Le thème de la sécurité des fondations a historiquement fait l'objet d'une attention particulière, dans la théorie et la pratique, en raison de la nécessité de trouver des solutions optimales entre coût et sécurité. La sécurité vis-à-vis des états limites ultimes est notamment importante dans le cadre des fondations sur pieux, par opposition aux autres types de fondations, dans lesquels les états limites de service dominent les considérations de sécurité. Cet article présente une nouvelle approche, dans laquelle l'inférence bayésienne est utilisée pour combiner les prédictions de capacité portante et les contrôles in situ, afin d'améliorer l'évaluation de la fiabilité et, éventuellement, conduire à un projet plus économique. Des procédures semi-empiriques fondées sur le SPT sont fréquemment utilisées pour la prévision de la capacité portante, et ce sont celles traitées ici. Le refus élastique et l'enfoncement obtenus au cours du battage des pieux sont généralement utilisés pour le seul contrôle de l'uniformité, mais cet article explore la possibilité de combiner ces informations, dûment interprétées, avec les prédictions de projet afin de parvenir à des fondations plus économiques, tout en maintenant le niveau prescrit de sécurité vis-à-vis de la rupture. L'extension de l'approche, au cas où des essais de chargement de pieux (statique et dynamique) sont également disponibles, est simple; elle est discutée dans les documents référencés.

KEYWORDS: pile, set, rebound, foundation, safety, bayesian, inference, ULS

1 INTRODUCTION

Foundation safety is a primary concern of civil engineers. Given the serviceability requirements of modern buildings, safety is frequently governed by serviceability limit states. Even if safety against such limit states must always be confirmed, pile foundations are most often designed on the basis of bearing capacity predictions, i.e., ultimate limit states. Semi-empirical procedures based upon field tests such as SPT or CPT are a common choice for such predictions.

The paper presents a new approach, in which Bayesian inference is used to combine bearing capacity predictions and field controls, so as to improve reliability assessment, and possibly lead to more economic design.

2 THE PROPOSED APPROACH

The idea behind the proposed approach is that foundation design based on semi-empirical bearing capacity prediction models can benefit from the incorporation of duly interpreted field controls during construction.

Even if field controls are almost always used exclusively to guarantee that uniform behavior is attained, it is believed that such controls carry quantifiable information that can be translated into more efficient foundation solutions.

The proposed incorporation mechanism is Bayesian updating. This paper relies heavily in the work of Baecher and Rackwitz (1982), which has been explored in detail by Santos (2007) and by Hachich and Santos (2006).

3 SEMI EMPIRICAL PREDICTION PROCEDURES

Bearing capacity prediction is one of the key analyses required by pile foundation design. Several semi-empirical procedures are available, based on different geotechnical investigation methods, such as SPT, CPT, pressuremeter, dilatometer, and others.

The use of the SPT to estimate bearing capacity of piles is still current practice in Brazil and other countries (Poulos et al. 2001). "Case 1" bearing capacity predictions, as categorized by Poulos (1989), are the commonly adopted procedure.

Several bearing capacity prediction methods using the SPT have been developed since Meyerhof (1956), including the relatively recent SPT 97, by the Florida DOT.

In Brazil the most widely used such method is D&Q, the Décourt and Quaresma method (Décourt and Quaresma 1978, Décourt 1982, Décourt 1991). For this reason, D&Q is retained in the paper as the ultimate load prediction method.

Table 1 presents the moments of the random variable $R=\log_{10}(K)$, where $K = P_{OBS}/P_{PRED}$. The first line is based on the values originally used to develop the method, where P_{OBS} was derived from static load tests on precast concrete piles and $P_{PRED}=P_{D\&Q}$. The second line is based on the statistical analysis of a database of 189 dynamic load tests in precast concrete piles

(Rosa 2000), revised to correlate static ultimate loads to CASE-dynamic ultimate loads (Bilfinger 2002).

Table 1. Moments of the distribution of R = log ($P_{OBS}/P_{D\&Q}$) from two different sources

Source	Mean	Variance
40 static load tests (original)	0.00610	0.01538
189 dynamic load tests reinterpreted	0.04157	0.04330

Figure 1 is a graphical representation of the distribution associated with the second line of Table 1.

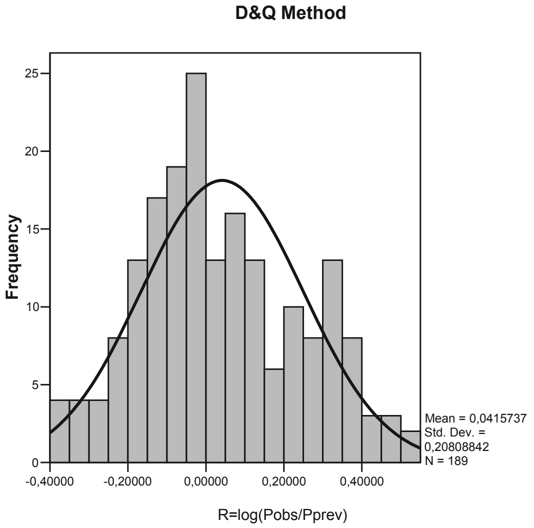

Figure 1. Distribution of R = log ($P_{OBS}/P_{D\&Q}$)

It is interesting to note that the variance of the original results used to develop the method is significantly lower than that associated with databases compiled from regular job sites. One can speculate that boreholes and tested piles were probably much closer to each other for the original formulation, so that intra-site variance was negligible. Moreover, the correlation between static and dynamic load tests adds to the uncertainty in the second database of Table 1. In any case, the higher coefficient of variation of $P_{OBS}/P_{D\&Q}$ in the second database (61.7%) is not incompatible with equivalent results found by other researchers: Briaud and Tucker (1988) published the results of 98 static pile load tests and showed that the coefficient of variation of P_{OBS}/P_{PRED}, for 12 different ultimate load prediction methods (using SPT, CPT, PMT and direct shear strength tests) varied between 42% and 74%.

For this reason, it seems reasonable to assume that ultimate load prediction methods based on industry-standard site investigation plans are prone to exhibiting high variability and could, therefore, benefit from information gathered during the pile driving operation itself.

4 FIELD CONTROL METHODS

Only a limited number of piles are usually subject to dynamic monitoring and testing. For the vast majority, field control methods are the only tools the engineer has at his disposal to check if the piles are being adequately driven.

Field control methods have been used since the early days of pile driving, and the best known is the set, the permanent settlement due to a hammer blow. There are a number of the so called pile driving formulas, which basically equate the energy delivered by the pile driving equipment to the work done by the soil forces that resist pile penetration.

Terzaghi (1943) thus expressed his realistic opinion about the relevance of those formulas: *In spite of their obvious deficiencies and their unreliability, pile driving formulas still enjoy great popularity among practicing engineers, because the use of these formulas reduces the design of a pile foundation to a very simple procedure.* The number of technical papers on such formulas is indeed significant; after all, it is also relatively easy to obtain field data. Even if some published results show good correlation between estimated and measured ultimate loads, the universal use of any particular formula must be questioned: pile length, pile diameter, hammer types, operational practices, soil types, to name a few, are factors which have significant impacts on the results. Figure 2 presents, for the database made available by Rosa (2000), the comparison of ultimate loads obtained by dynamic load tests and those predicted on the basis of some of the most popular (Poulos and Davis 1980) set-based pile driving formulas: Engineering News, Eytelwein (or Dutch), Weisbach, Hiley, Janbu, Danish and Gates. The scatter speaks for itself.

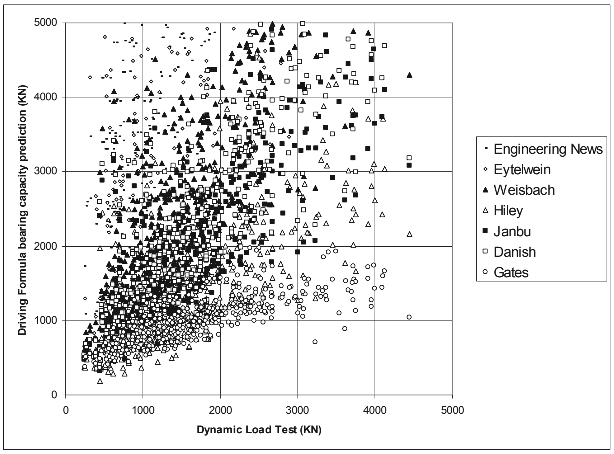

Figure 2. Comparison between measured and estimated bearing capacities using set-based dynamic formulas.

Janbu's formula led to the best correlation and the moments of the variable log(P_{OBS}/P_{CTL}), where CTL=Janbu, are presented in table 2.

Rebound, the elastic deformation caused by a hammer blow, is being increasingly used as a pile driving field control. The basic idea is to use the pile itself as a dynamometer that measures soil resistance to driving, but it is sometimes difficult to distinguish pile rebound from soil rebound. Moreover, measuring rebound requires continuous pile displacement recording during driving, which is more complicated than set measurement.

Figure 3 presents, for the database made available by Rosa (2000), the comparison of ultimate loads obtained by dynamic load tests and those predicted on the basis of two of the most popular (Aoki and Alonso 1989) rebound-based pile driving formulas: Chellis and Uto. In addition, it presents similar results for Rosa's modification of the Chellis formula (Rosa 2000). Comparison of the scatter in Figures 2 and 3 suggests that rebound-based formulas are more precise than set-based formulas. This is confirmed by the variances in Table 2. Also, the coefficient of variation of P_{OBS}/P_{JANBU} is 69.8%, while that of $P_{OBS}/P_{CHELLIS}$ is 45.0%.

Table 2. Moments of the distribution of log (P_{OBS}/P_{CTL}) for two different formulas

Pile driving formula	Mean	Variance
CTL=Janbu (set-based)	-0.01819	0.02657
CTL=Chellis (rebound-based)	0.01818	0.01113

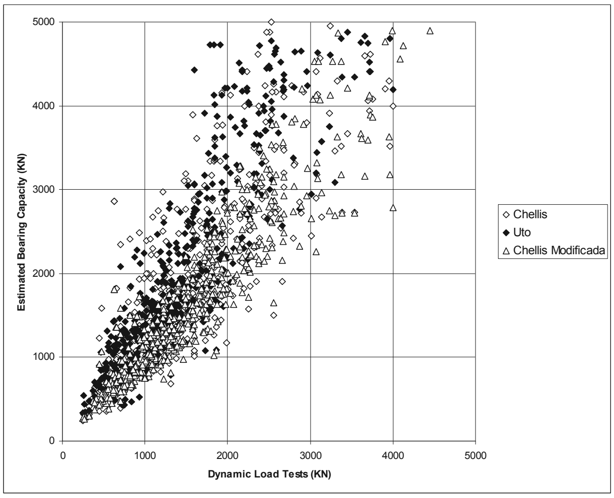

Figure 3. Comparison between measured and estimated bearing capacities using rebound-based dynamic formulas.

5 BAYESIAN UPDATING IN PILE FOUNDATION SAFETY

Baecher and Rackwitz (1982) define a random variable K = P_{OBS}/P_{PRED} as the ratio of observed and predicted resisting forces, which is assumed to follow a lognormal distribution. Therefore, R=$\log_{10}$(K) is normally distributed (Gauss): R~N(ρ,h^{-1}), where ρ and h^{-1} are the usual parameters of a Gaussian distribution; ρ represents the central tendency and h^{-1} the dispersion. In more usual notation, $h = 1/\sigma^2$, that is, parameter h, which is sometimes called precision, is the inverse of the variance. In the context of Bayesian inference, the parameters of $f_R(r)$, ρ and h, are themselves random variables, so that the (normal) distribution of R is conditional on the knowledge of those parameters: $f_R(r|\rho,h)$. Within this approach:

$$f_R(r) \propto \int_{\rho,h} f_R(r \mid \rho,h)\cdot f(\rho,h)\,d\rho dh \tag{1}$$

The Bayesian updating procedure consists in deriving a posterior (or updated) distribution $f''(\rho,h)$ from the prior distribution, $f'(\rho,h)$, and statistics of a sample obtained in the field. Formally,

$$\mathrm{f}''(\rho,\mathrm{h}) = \frac{\mathrm{L}(\rho,\mathrm{h})\cdot \mathrm{f}'(\rho,\mathrm{h})}{\int_{-\infty}^{\infty} \mathrm{L}(\rho,\mathrm{h})\cdot \mathrm{f}'(\rho,\mathrm{h})\mathrm{d}\rho\mathrm{dh}} \tag{2}$$

$f''(\rho,h)$ is the substituted into equation 1, so as to arrive at an updated version of $f_R(r)$.

Variability inherent to geological characteristics of the local subsoil, driving details and other local and circumstantial specificities make σ^2 vary from one site to the next; h is therefore named intra-site precision. Bilfinger and Hachich (2006) analyze some aspects of intra-site variability. Baecher and Rackwitz (1982) treat it as a random variable within the context of Bayesian inference (see equation 2). Many authors have treated variance as a known, generally estimated, deterministic parameter (Kay 1976, Kay 1977, Vrouwenvelder 1992, Zhang 2004). This is the approach adopted here.

Under such conditions of know variance, updating of a Normal process is significantly simpler and it can be demonstrated (Martz and Waller 1982) that the posterior distribution of ρ, the mean of $f_R(r)$, is also normal with two parameters obtained from equations 3 and 4.

$$h''_\rho m''_\rho = h'_\rho m'_\rho + n\cdot h\cdot \bar{r} \tag{3}$$

$$h''_\rho = h'_\rho + n\cdot h \tag{4}$$

The same authors (Martz and Waller 1982) show that, in the case of known variance, integration of the single nuisance parameter (ρ) leads to a predictive distribution of R (equivalent to equation 1) that is also Normal, with same posterior mean (equation 5) and a variance that satisfies equation 6.

$$m''_R = m''_\rho \tag{5}$$

$$\frac{1}{h''_R} = \frac{1}{h''_\rho} + \frac{1}{h} \tag{6}$$

The procedure described above can be readily applied to a situation in which the new information stems from a direct measurement of the resisting force (P_{OBS}), such as a static or dynamic load test (Hachich and Santos 2006, Hachich, Falconi and Santos, 2008).

In this paper, however, the idea is to incorporate whatever information is provided by field control procedures into the reevaluation of the safety of a pile foundation. The resisting force on a pile, P_{PRED}, is predicted at the design stage by one of the semi-empirical procedures, which are based on SPT blow counts from a borehole that is seldom located at the exact point where the pile is being installed. The only information pertaining exactly to the location where the pile is installed is provided by the field control procedures, either set or elastic rebound, and it would be a waste not to take advantage of this location-specific information to revise the pile safety prediction.

For this, P_{OBS}/P_{PRED} can be written as the product of P_{OBS}/P_{CLT} and P_{CTL}/P_{PRED}, where P_{CTL} stands for the pile resistance inferred from the field control records, namely Janbu's expression based on set, or Chellis expression based on rebound. It is straightforward to derive the moments of P_{OBS}/P_{PRED} from the moments of P_{OBS}/P_{CLT} and P_{CTL}/P_{PRED}. It is understandable that the variance of P_{OBS}/P_{PRED} thus obtained is significantly larger than the variance of the P_{OBS}/P_{PRED} derived from pile resistances actually measured in pile load tests. This fact must be accounted for in the Bayesian updating procedure, since the actual observation is not a pile load test, but rather an estimate of ultimate load based on a field control measurement. It can be demonstrated that this is achieved in a statistically sound manner if the actual number of observations (n in equations 3 and 4) is replaced by an equivalent number that is adjusted downwards in proportion to the ratio of those two variances. In other words, one observation derived from a set measurement and application of Janbu's formula (or rebound and Chellis), is worth less than one observation in the Bayesian updating procedure.

The moments of P_{OBS}/P_{CTL} are available from the proponents of the pile driving formulas and from correlation studies in the literature. Values relevant to the present application were presented item 4 above.

Moments of P_{CTL}/P_{PRED} are the only missing piece of information for application of the Bayesian updating procedure just proposed.

Table 3 presents the moments of the random variable log ($P_{CTL}/P_{D\&Q}$), estimated from statistical analysis of the aforementioned database of 189 dynamic pile load tests (Rosa 2000), revised by Bilfinger (2002) to correlate static ultimate loads to CASE-dynamic ultimate loads. The database includes precast concrete piles with diameters of 17 to 70cm, lengths up to 39m, driven by free fall hammers of 13 to 80kN. The first line of Table 3 refers to the variable log($P_{JANBU}/P_{D\&Q}$), while the second refers to log($P_{CHELLIS}/P_{D\&Q}$).

Table 3. Moments of the distribution of R = log ($P_{CTL}/P_{D\&Q}$) for Janbu and Chellis formulas

Pile driving formula	Mean	Variance
CTL=Janbu (set-based)	0.05977	0.05339
CTL=Chellis (rebound-based	0.02339	0.04523

Once again correlations with the Chellis formula exhibit a smaller variance that those with Janbu's.

6 APPLICATION AND RESULTS

Application of the proposed procedure was guided by the final goal of developing plots that could provide sound statistical justification to field operational rules that will lead to more economical pile foundation solutions, such as shorter piles, with the very same probability of failure (or reliability index, β).

Figures 4 and 5, developed by means of equations 3 to 6 with data from Tables 1 to 3, show the updated global safety factor required to maintain the same reliability index (β) after the distribution of the predicted ultimate load of the pile is updated on the basis of field control measurements and the corresponding pile driving formulas. The x-axis values are possible observable results of the ratio P_{OBS}/P_{PRED}. In Figure 4, set is the field control and Janbu is the formula used for P_{OBS} prediction. In Figure 5 the performance of set and rebound are compared for an intra-site variance of 0.08, while results in Figure 4 explore four possible values of intra-site variance.

Figure 5 confirms previously discussed indications that rebound-based control is slightly superior to set-based control.

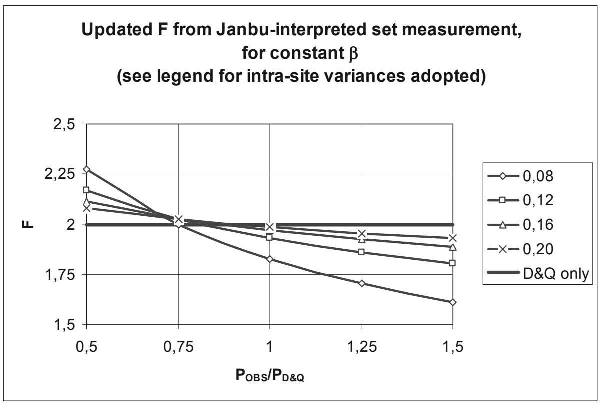

Figure 4 - Comparison of code-prescribed global safety factor (F=2) with set-updated F values, for the same reliability index (β)

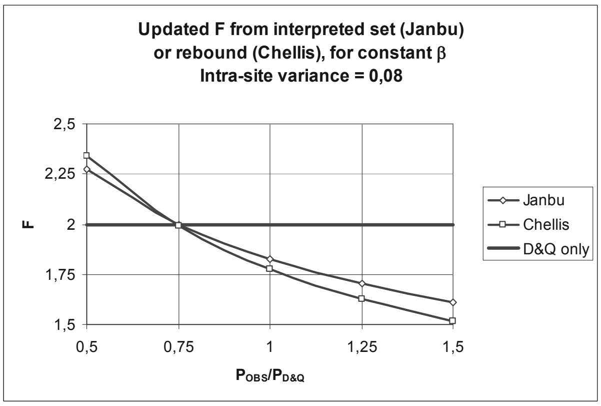

Figure 5 - Comparison of the performance of set and rebound field controls for updating the safety factor while preserving the same reliability index (β)

7 CONCLUSIONS

Duly interpreted field control measurements, recorded during pile driving, facilitate more economical pile foundation design, while maintaining the same safety level required by code-prescribed safety factors. Figure 5, for example, sets a sound foundation for operational rules that provide safe guidance for early interruption of pile driving.

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