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Calibration of resistance factors for driven piles using local data from an Argentinian site

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ABSTRACT: Argentina is debating the implementation of the Load and Resistance Factor Design (LRFD) in the geotechnical design code. Therefore, the investigation of resistance factors in geotechnical designs is needed throughout the entire national territory, since it is necessary to use local information of soil and tests records to calibrate resistance factors (ϕ). This work presents a calibration of resistance factors (ϕ) for driven piles in cohesive soils using local data from a specific site in Buenos Aires, Argentina. The data consists in an extensive site characterization, driving records during execution of piles and dynamic load tests using correlation signal analysis. Finally, First Order Second Moment (FOSM), First Order Reliability Method (FORM) and Monte Carlo simulation were used to calibrate ϕ for reliability index of β=1.75 to 3.5, and for several capacity prediction methods such as: α, β and λ methods, dynamics formulas and Schtmertman and Shioi and Fukui SPT prediction methods. Factors for static load tests were also calibrated, considering different levels of soil variability. Results obtained in these analyses, suggests that the procedure followed improve reasonably the ϕ values in comparison with those recommended by the AASHTO regulations for each prediction method at local conditions analyzed.

RÉSUMÉ: L'Argentine est en train de débattre l'implémentation des facteurs de charge et de résistance (LRFD) dans le code national de géotechnique. Par conséquent, l'étude de l'applicabilité des facteurs de résistance dans les conceptions géotechniques est néces-saire sur tout le territoire national, car il faut utiliser les informations locaux sur les sols et les enregistrements d'essais pour calibrer les facteurs de résistance. Ce travail présente un étalonnage des facteurs de résistance (ϕ) pour des pieux battus dans des sols cohérents en utilisant des données locales d'un site spécifique de la ville de Buenos Aires, Argentine. Les données consistent en une large caractérisation du site, que contient des enregistrements lors de l'exécution des pieux et en des tests de charge dynamique utilisant l'analyse de corrélation des signaux. Enfin, le Premier Ordre Second Moment (FOSM), la Méthode de Fiabilité du Premier Ordre (FORM) et la simulation Monte Carlo ont été utilisés pour calibrer ϕ pour un indice de confiabilité de β = 1,75 à 3,5, et pour plusieurs méthodes de prédiction de capacité telles que: α, β et λ méthodes, formules dynamiques et méthodes de prédiction Schtmertman et Shioi et Fukui (SPT). Les facteurs de resistance pour le test de charge statique ont été aussi calibrés, en considerant des differents niveaux de variabilité du sol. Les resultats obtenues dans le présent étude, demontres que le procediment suivi, a amellioré les valeurs des facteurs qui recommend le reglament ASSHTO pour les differents methodes de prediction en considerant les conditions locaux.

KEYWORDS: LRFD, Reliability analysis, Driven piles, Cohesive soils, Resistance factors.

1 INTRODUCTION.

The method based on Limit States, applied by Load and Resistance Factor Design (LRFD) to the design of foundations currently represents the most widely used methodology in the main countries of the world. Regulations for the design of bridges such as AASHTO (American Association of State Highway and Transportation Officials), Eurocode 7 and The Australian Standard for Piling-Design and Installation (1995) have implemented it with a high degree of acceptance, succeeding in replacing design by allowable stresses design (ASD).
Currently the creation of a geotechnical design code is being debated in Argentina, including as a foundation design method the Load and Resistance Factor Design (LRFD) (Eq. 1) (AASTHO, 2017), which would replace the Allowable Stress Design method (ASD) (Eq. 3), which is the design method with which foundations are calculated and verified since the beginnings of geotechnical engineering in the country.

$$\phi R_n \geq \sum \eta_i \gamma_i Q_i \quad (1)$$

Where:

$$\eta_i = \eta_D \eta_R \eta_I > 0.95 \quad (2)$$

ϕ	Resistance factor,
R_n	Ultimate resistance,
η_i	Load modifier,
γ_i	Load factors,
Q_i	Applied loads,
η_D	Factor that takes into account ductility effects,
η_R	Factor that takes into account redundancy effects,
η_I	Factor that takes into account operational importance.

$$Q_{all} = \frac{R_n}{FS} = \frac{Q_{ult}}{FS} \quad (3)$$

Where:

Q_{all}	Allowable design load,
R_n	Resistance of the element or the structure,
Q_{ult}	Ultimate geotechnical resistance,
FS	Global safety factor.

Therefore, the universities involved as well as the entity in charge of creating the geotechnical design code, are carrying out an extensive study and assimilation of the LRFD design philosophy. The application of the resistance factors to the design of foundations, is something new in local practice, and there is not enough knowledge of how to obtain and apply them, nor of the relationship that designs carried out through LRFD can keep with respect to the designs developed by the traditional theory of allowable stresses, based on the use of the global safety factor (FS) (Paikowsky *et al*., 2004).
The design using LRFD (Eq. 1) proposes the use of load and resistance factors, taking into consideration the degree of variability of the loads and resistances separately, according to the degree

of uncertainty that these have. The proposed factors are in accordance with a level of reliability established in advance for the design.

There is a lot of background of resistance factors calibrations for LRFD based on dynamic tests, one of them is the one carried out by The Missouri Department of Transportation (MoDOT) (Stuckmeyer et al., 2013) and the one carried out to propose resistance factors for the National Building Code of Iran (Asghari Pari et al., 2019).

In the present investigation the calibration of resistance factors (ϕ) was developed for reinforced concrete piles driven in clays. For this, a database provided by the company Soletanche Bachy Argentina is used. This database has information of 2 projects that contain piles driven into clay soil, and in which dynamic tests (CAPWAP) were carried out to verify their geotechnical resistance. The database also has soil characterization studies, triaxial tests and in-situ tests such as the Standard Penetration Test (SPT).

The calibration of resistance factors were carried out by the most applied methods based on reliability theory, which are the First Order Second Moment (FOSM), First Order Reliability Method (FORM) and Montecarlo simulation (MCS). The reference resistance used in the calibrations of the different resistance prediction methods is the resistance obtained from the dynamic tests (CAPWAP- BOR), since a significant number of static load tests on driven piles were not available to build a robust database for calibrations.

Through the use of auxiliary databases the existing correlations in the determination of the resistance of driven piles through static load tests and dynamic tests were also investigated. Based on these correlations, the available database was adapted, introducing in the calibrations the margin of error that implies determining the resistant factors ϕ from the results of dynamic tests.

The pile data with which the NCHRP 24-17 report (Paikowsky et al, 2004) was prepared, provided by the authors of said report, has been used as auxiliary databases. Information was also obtained from the Federal Highway Administration (FHWA) database called "Deep Foundation Load Test Database" (Shesh K, et al, 2013).

The main resistance prediction methods used in the local practice have been evaluated for driven piles in clay and the most representative methods have been chosen in order to calibrate the resistance factors.

The methods for which the factors are calibrated are divided in four groups: a). *Static or semi-empirical analysis methods* (α-Tomlinson, α-API, β-Burland, λ Vijayvergiya y Focht, Brinch Hansen and Janbu), b). *Dynamic formulas* (Hiley's formula), c). *In-situ analysis methods* (SPT- Schmertmann and SPT- Shioi and Fukui), and d). *Field tests* (CAPWAP and static load test).

Different levels of reliability are chosen, in order to be able to represent the variation of the resistance factors with the level of reliability expected for the design.

2 DEVOLOPEMENT AND SELECTION OF DATABASE.

The database that has been utilized consists of 35 precast reinforced concrete piles driven into clays with the tip in a dense sand stratum, 25 to 35 meters long, with a square section of 0.30 x 0.30 m. The total number of piles are part of 2 infrastructure projects which are located in Buenos Aires.

The stratigraphy in which the driven piles were installed is shown in Fig. 1. The piles cross predominantly clayey soils: *Post-Pampeano* and *Pampeano*, reaching the tip of them the *Puelches* sand layer. The clayey fraction of the soils (*Postpampeano* formation) is composed of clays of high plasticity type CH and MH, and with a relative compactness corresponding to "soft" to "very soft" soils (Sfriso, 1995).

The layer corresponding to the *Pampeano* formation consists of a modified loess, strongly preconsolidated by drying and cemented by carbonates (Bolognesi, 1975). The third stratum analyzed, consists of *Puelches* sands, composed of dense to very dense fine sands, with high mechanical competence.

In order to perform a comparative analysis between databases and have reference values, the analysis, processing and filtering of two additional databases have been carried out, which due to their level of available information, were taken as a reference for the calibration process carried out in the present study. In this way, with the information obtained from them, an auxiliary database was created.

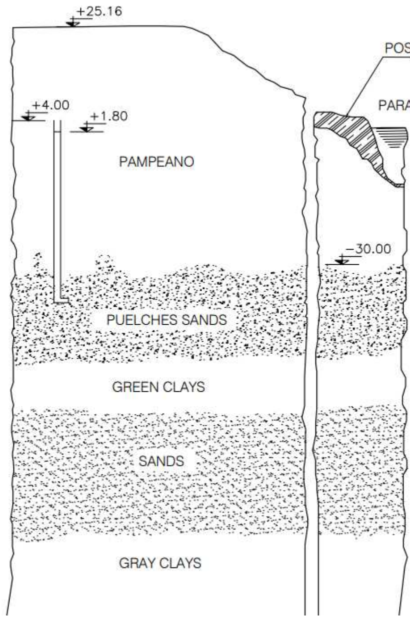

Figure 1. Typical soil profile of the pile implantation area (work adaptation of Bolgnesi, 1975)

The first database consists of information of driven piles from which the calibrations of the resistance factors recommended in the report NCHRP 24-17 Load and Resistance Factor Design (LRFD) for Deep Foundations were performed (Paikowsky et al, 2004). It consists of static load tests and dynamic tests, and that gathers information from 77 different infrastructure works, with a total of approximately 890 tested piles.

The second database consists of deep foundations and is named "Deep Foundation Load Test Database" (Shesh K. et al., 2013). It was conducted by the Federal Highway Administration (FHWA) and contains information on more than 1,500 deep foundations, of more than 850 infrastructure projects. It contains not only load tests, but also results of in situ tests (SPT and CPT), results of laboratory tests, characteristics of the piles, etc.

Both databases described have been filtered in order to obtain useful information for the present study. In this way, those driven piles were selected, with a shaft in clay soil and a tip in sand, with a length between 6 to 39 m, square section and with an areal ratio (shaft area/tip area) between 100 to 350. With the information obtained, an auxiliary database to the main one was set up, from which reference variables were obtained that were used to perform the calibrations. The main variable of interest obtained from the auxiliary database is the relationship between the resistance obtained by static load test vs the resistance obtained by CAPWAP dynamic tests.

3. AXIAL PREDICTION METHODS EVALUATED

All the alternatives used in local practice were analyzed to determine the ultimate load capacity of driven piles, and those methods that are more representative and that have greater use and dissemination in the field of practice were selected. In this way, the ultimate strengths were determined using (1) static analysis methods based on soil properties, (2) dynamic formulas, based on the driving records, (3) in situ or empirical analysis methods, (4) dynamic tests and (5) static load tests.
Static analysis methods are mainly based on the determination of the ultimate bearing capacity of piles through relationships be-tween soil properties (undrained cohesion S_u, overconsolidation relationship, etc.) and proportionality factors specific to each method. The static methods chosen for the determination of shaft resistance, assuming that it is mainly clayey soil, are α-Tomlin-son, α-API, β-Burland and λ Vijayvergiya and Focht. For the de-termination of the toe resistance, assuming that it is installed on a dense sand layer the Brinch Hansen and Janbu methods were selected.
The dynamic formula chosen in the present study is the Hiley's formula, which takes into account the measurement of the rejection of the pile at the moment of driving, and also considers the energy used to install the pile.
The selected in-situ analysis methods, according to the type of soil, correspond to SPT- Schmertmann and SPT- Shioi and Fukui, since they provide correlations for both clay and sandy soils.
The dynamic tests chosen are those that perform measurements using a Pile Driving Analyzer (PDA) and that estimate resistance using the signal matching technique, using the Case Pile Wave Analysis Program (CAPWAP) method, in the End Of Drive (EOD) and Beginning Of Restrike (BOR) stages.
Static load tests (SLT) are analyzed according to the variability of the site where the test takes place. Different values of variability are analyzed (low, medium and high), and it is quantified through the value of the coefficient of variation (COV). Thus, for low variability, the COV is 0.15, for medium variability, 0.25, and for high variability, 0.35. These values have been taken from the studies carried out by Kulhawy *et al*. (1996).

4 CALIBRATION OF RESISTANCE FACTORS BY RELIABILITY THEORY

The calibration of the resistance factors was carried out by Reliability Based Theory (RBD), which considers the concepts of uncertainty and risk in the design in mathematical terms through which, both the term of loads Q_i and resistance R_n (Eq. 1) are considered as random variables.
The risk in the design is quantified by the probability of failure (P_f) which is obtained from a failure function in which these random variables intervene. In this way, the objective of this methodology is that the probability of failure of the designed component does not exceed an acceptable limit level (Phoon & Kulhawy, 1996). Resistance factors have been calibrated by three different calibration methods: FOSM, FORM and MCS, for different levels of reliability.

4.1. Selection of reliability index.

The reliability is directly associated to the probability of failure that the design will have (Kuo et al.,2003). It depends mainly of the consequences of the failure, importance or level of service of the construction, useful life of the structure and other political, social and economic factors.
For the selection of the reliability levels (β) for which the resistance factors were calibrated, a background analysis and a study of the values used by existing design codes were performed. For example, the reference values for the level of reliability used by AAHSTO for the design of groups of driven piles, results of β = 2.33. The AASHTO code recommends that, for the design of individual piles, the recommended factors (calibrated for a value of β = 2.33) be reduced by 20% which is associated with a level of reliability of β = 3.00.
In the case of factor calibration, under the load state that considers the seismic action, Foye and Salgado (2004) recommend a reliability value of β = 1.75.
In order to make the design compatible with designs made using the Allowable Stress Design (ASD), the reliability values β of geotechnical designs based on ASD have been investigated. Barker *et al*. (1991) have provided the following reliability indices for driven piles:

- Meyerhof (1970), showed that the probability of failure of foundations can vary between 10^{-3} and 10^{-4}, which corresponds to values of β between 3.00 and 3.60.
- The reliability values for driven piles are in the order of 1.50 to 2.80. Therefore, values of β between 2.50 and 3.00 may be appropriate.
- For pile groups, the failure of a pile does not necessarily imply the failure of the group. Due to this redundancy in pile systems, it is considered that the target reliability can be reduced from 2.50 to 3.00 to values between 2.00 to 2.50.

In summary, and based on the considerations mentioned above, the reliability values associated with the different levels of probability of failure used is shown in Table 1.

Table 1: Relationship between reliability index and probability of failure

Reliability Index β	Probability of faulure Pf = Φ(-β)
1,75	0,04006
2,33	0,00990
3,00	0,00135
3,50	0,00023

Φ(·)= probability distribution

4.2 Load factor characteristics.

The current regulations for the design of civil structures in Argentina are based on the LRFD method, using resistance factors for structural components and load factors for different acting loads. In order to make the design of foundations compatible with the structural design, the values of load factors used in the structural design are used for the current calibration of resistance factors.
Since the design of foundations in Ultimate Limit State (ULS) is mainly conditioned by permanent loads "DL" and live loads "LL", these loads factors and load states are used in the current calibration process. The values of the load factors γ_i used are shown in Table 2, with the mean values and coefficient of variation of the bias of loads. These last values are developed in the publication made by the ASCE called "Probability based load criteria: Assessment of current design practice" (Galambos *et al*., 1982).

Table 2: Probabilistic values of the load factors.

Type of load		Load Factor γ	Bias λ	Coeficient of variation COV
Dead load	DL	1,20	1,05	0,10
Live load	LL	1,60	1,10	0,25

4.3 Calibration theories utilized.

When statistical data are available calibrations can be carried out using reliability theory (Murad *et al*, 2009). The resistance factors chosen for a particular limit state must take into account according to Withiam *et al*. (1998):

a) Variability of soil and rock properties,
b) Uncertainty of the equations used to predict resistance,
c) Quality of the workmanship employed,
d) Extent of on-site explorations (specific or extensive),
e) Consequences of failure.

To take into account the inherent uncertainties of resistances and loads in a consistent way, three calibration methods based on reliability theory were used, which are explained in summary below (Kuo et al., 2003.).

The first method, First Order Second Moment (FOSM), linearizes the limit state function in a series of Taylor expansions on the mean value of the variable (Murad et al, 2009). The calculation of the resistance factors by this method is carried out by applying a closed formula, which involves the value of the probabilistic variables (mean and coefficient of variation) of the terms of loads and resistances and the level of reliability required.

The FORM method (First Order Reliability Method) requires knowledge of the probability distributions and the values of mean and coefficient of variation of the variables involved in the calibration process (loads and resistances) (Murad et al, 2009). It is based on the choice of a control point, called "design point", which results in a particular point on the boundary state surface $g(x)= R_i-Q_i$, in which $g(x)= 0$. The objective reliability β for which the calibration is being carried out results the separation between the design point and the mean of the resistance data set. The method determines the reliability β geometrically as the shortest distance from the mean values of the variables to the point closest to the established failure criterion in normalized normal space (Hasofer and Lind, 1974).

The Montecarlo simulation proposes to evaluate the failure function $g(x)=R_i-Q_i$ a large number of times, associated with the failure probability to be achieved. The function is evaluated using different values between 0 and 1, normally distributed and randomly generated. In this way, using a random number generator, values of the cumulative distribution are extrapolated for each random variable (Murad et al, 2009). The probability of failure associated with the proposed resistance factors is determined as the number of times that the failure function $g(x)$ is less than zero $g(x)<0$, with respect to the total number of simulations carried out.

The resistance factors obtained through the three calibration methods, and for different levels of reliability can be seen in Table 3. The probability distributions of the bias λ (measured resistance/estimated resistance) are lognormal. To verify the quality of fit of the distribution to the data sample, an Anderson-Darling goodness of fit test was performed, obtaining that in all cases, the distribution that best fits the calibration data is lognormal.

4.4 Adaptation of database to dynamic methods for calibration.

The database with which the resistant factors are calibrated is composed of dynamic test results such as CAPWAP- BOR (Beginning Of Redrive).

Static load tests (SLT), from which the reference resistance is obtained in conventional calibrations of resistance factors are very limited in the local practice, due to their high cost and complexity of execution. Due to this lack of static test results, it was not possible to collect a sufficient quantity to carry out factor calibrations. In this way, the reference resistance or "measured resistance" used in the calibrations is the dynamic resistance from tests CAPWAP-BOR.

To consider the margin of error in the determination of resistance factors (ϕ) from the results of dynamic tests, with respect to those that would be obtained if they were calibrated through static tests, the values of the input variables of the calibrations are modified. The modification is made on mean λ_i and coefficient of variation COV_i of the bias. To match the difference between CAPWAP and SLT, the following operations are performed (Grubb et al., 2007):

$$\lambda_R = \lambda_i \; x \; \lambda_{SLT/CW} \quad (4)$$

$$COV_R = \sqrt{COV_i + COV_{SLT/CW}} \quad (5)$$

Where:

λ_R	Modified bias mean,
λ_i	Mean of the bias based on CAPWAP,
$\lambda_{SLT/CW}$	Mean of the bias between SLT and CAPWAP,
COV_R	Modified coefficient of variation,
COV_i	CAPWAP-based coefficient of variation,
$COV_{SLT/CW}$	Coefficient of variation between SLT and CAPWAP.

The calibrations were carried out with the values of λ_R and COV_R. The $\lambda_{SLT/CW}$ and $COV_{SLT/CW}$ values were obtained from the auxiliary database, which was filtered for driven piles in clays.

Based on the auxiliary databases, the relationships between resistances measured by static load tests and by CAPWAP were obtained. The correlations obtained are similar to those developed in the report "Correlation of CAPWAP with static load test" by Likins and Rausche (2004).

5. ANALYSIS OF CALIBRATION RESULTS.

Different values of resistance factors were obtained for the prediction methods evaluated. Analyzing the values of the input variables λ_R and COV_R of the calibrations (Table 3), it is appreciated that in most cases the λ_R bias values are higher than 1.00, which implies that the methods are underestimating the resistance of the piles.

It can also be seen that as the value of the bias increases, the resistance factors become greater, which implies that the methods that tend to underestimate the resistance have a greater resistance factor associated with it and vice versa.

The coefficient of variation COV_R takes moderate values (less than 0.30) in methods that have a better estimate of resistance, and higher values for those methods that have many dispersions in their results.

Regarding the comparison of factors obtained through the different calibration methods, it can be seen that they have little difference between them, the largest difference is of the order of 16%, between the FOSM and MCS methods. The method that provides the greatest resistance factors is the Montecarlo simulation.

As expected, as the required level of reliability increases, the value of the resistance factors is reduced, taking half their value between the reliabilities β = 1.75 and β = 3.00. This variation shows that the resistance factors do not have a linear relationship with the reliability level β.

In relation to the values obtained, it can be seen that the static analysis methods based on soil properties (α, β, λ, Brinch Hansen and Janbu) show resistance factors in the order of 0.44 to 0.63 (for β = 1.75).

Table 3: Calibrated resistance factors ϕ.

Prediction metthod	Estimated resistance	N. of data	R	COV_R	β= 1,75			β= 2,33			β= 3,00			β= 3,50		
							c			c			c			c
α- Tomlinson	Skin frictional	24	1,30	0,54	0,54	0,58	0,60	0,39	0,43	0,44	0,27	0,30	0,31	0,20	0,23	0,24
α- API	Skin frictional	22	1,11	0,50	0,50	0,54	0,48	0,36	0,39	0,35	0,25	0,26	0,24	0,19	0,22	0,18
β- Burland	Skin frictional	24	1,56	0,56	0,63	0,66	0,60	0,45	0,49	0,43	0,30	0,30	0,28	0,23	0,26	0,21
λ- Vijayvergiya y Focht	Skin frictional	23	1,47	0,52	0,63	0,68	0,61	0,46	0,50	0,44	0,31	0,32	0,30	0,24	0,27	0,23
Brinch-Hansen	End bearing	19	1,16	0,60	0,44	0,46	0,42	0,31	0,33	0,29	0,20	0,20	0,19	0,15	0,16	0,14
Janbu	End bearing	19	1,68	0,67	0,56	0,59	0,53	0,38	0,41	0,36	0,25	0,25	0,23	0,18	0,19	0,16
Hiley formula	Total	10	0,48	0,60	0,18	0,19	0,17	0,13	0,14	0,12	0,09	0,09	0,08	0,06	0,07	0,05
SPT-Schmertmann	Total	34	1,46	0,48	0,68	0,70	0,65	0,50	0,55	0,48	0,35	0,37	0,33	0,27	0,31	0,26
SPT- Shioi y Fukui	Total	15	0,88	0,41	0,46	0,50	0,45	0,35	0,39	0,34	0,25	0,27	0,25	0,20	0,24	0,20
CAPWAP (EOD)	Total	37	1,86	0,57	0,74	0,77	0,71	0,53	0,58	0,50	0,35	0,36	0,34	0,26	0,29	0,25
CAPWAP (BOR)	Total	22	1,13	0,27	0,73	0,82	0,75	0,59	0,70	0,62	0,46	0,54	0,49	0,38	0,48	0,41
SLT- Low variability	Total	-	1,00	0,15	0,75	0,89	0,80	0,63	0,80	0,69	0,51	0,68	0,58	0,44	0,63	0,52
SLT- Medium variability	Total	-	1,00	0,25	0,67	0,76	0,68	0,54	0,66	0,56	0,42	0,51	0,45	0,35	0,46	0,38
SLT- High variability	Total	-	1,00	0,35	0,57	0,64	0,57	0,45	0,51	0,45	0,34	0,37	0,33	0,27	0,34	0,27

Resistance factor based on FOSM
Resistance factor based on MCS
^{c} Resistance factor based on FORM

These results show that the performance of static methods is strongly influenced by the way in which the soil properties are obtained, the test conditions and the theoretical framework on which the method is based (Asghari Pari et al., 2019). In this way, as better correlations of soil properties are obtained, the more precise these methods become.

The reduction factor obtained for the driving formula is very low, showing that this formula has a low level of precision in estimating resistance, due to the high degree of dispersion of its results.

The analysis methods based on in situ correlations, SPT-Schmertmann and SPT-Shioi and Fukui, showed superior resistance factors compared to the static methods. This is mainly due to the fact that the dispersions are reduced obtaining a lower COV_R value.

Regarding the load tests, the CAPWAP dynamic tests and the static load tests (SLT) were evaluated. From the factors obtained it is evident that the dynamic CAPWAP test produces good predictions when the results of tests are taken in BOR, since the dispersions of the method decrease. It can be appreciated that the resistance factors for CAPWAP are superior to those corresponding to static methods or in-situ tests.

Finally, the factors obtained for SLT vary according to the coefficient of variation evaluated: the "low", "medium" and "high" variability is associated with COV_R values of 0.15, 0.25 and 0.35 respectively. In this way, the resistance factors have a maximum variation between the extremes "high" vs "low" of the order of 28%.

In Table 4, the efficiency factors ϕ/λ_R can be seen. This factors represent the used percentage of the resistance measured by a static load test provided by the prediction method. It is a more approximate value to be able to compare the performance of the prediction methods.

Analyzing the efficiency factors obtained, it can be seen that the most efficient resistance prediction methods (in order from best to worst prediction) are: the static load test, followed by the CAPWAP-BOR dynamic test, then the resistance prediction methods using SPT correlations, and finally the static methods.

The methods with the worst ϕ/λ_R values are the Janbu and Brinch-Hansen tip capacity determination methods and the Hiley dynamic formula.

Table 4: Efficiency factors ($\frac{\phi}{\lambda_R}$)of calibrated methods.

Prediction metthod	β= 1,75	β= 2,33	β= 3,00	β= 3,50
	ϕ/λ_R	ϕ/λ_R	ϕ/λ_R	ϕ/λ_R
α- Tomlinson	0,45	0,33	0,23	0,18
α- API	0,49	0,35	0,23	0,20
β- Burland	0,42	0,31	0,19	0,17
λ- Vijayvergiya y Focht	0,46	0,34	0,22	0,18
Brinch-Hansen	0,40	0,28	0,17	0,14
Janbu	0,35	0,24	0,15	0,11
Hiley formula	0,40	0,29	0,19	0,15
SPT-Schmertmann	0,48	0,38	0,25	0,21
SPT- Shioi y Fukui	0,57	0,44	0,31	0,27
CAPWAP (EOD)	0,41	0,31	0,19	0,16
CAPWAP (BOR)	0,73	0,62	0,48	0,42
SLT- Low variability	0,89	0,80	0,68	0,63
SLT- Medium variability	0,76	0,66	0,51	0,46
SLT- High variability	0,64	0,51	0,37	0,34

6. DISCUSSION AND CONCLUSIONS.

In this investigation, a database of driven piles in clays was created in order to obtain the resistance factors for various reliability values and through various calibration techniques.

The objective of the calibration was to obtain resistance factors that reflect the technological and engineering level of the local practice. An auxiliary database was also utilized, in order to generate a support for the calibrations carried out.

The reference resistance used in the present study for the calibration of resistant factors, is the corresponding to the results of dynamic test CAPWAP-BOR. To adapt the actual calibration to traditional methods, in which the reference resistance is based on static load tests, the values of the input variables λ_i and COV_i were scaled in order to consider the existing dispersions between CAPWAP and SLT.

From the results obtained, it is concluded that the methods that best predict the resistance of driven piles are the methods based on load tests, firstly static tests and secondly dynamic tests. Methods based on correlations with in situ tests such as SPT produce acceptable results.

In relation to the static methods, low values of resistance factors have been obtained in general, and the worsens condition for the dynamic formula, so it is recommended to accompany the design of piles using these methods, by a load test to ensure a better level of reliability.

From the results obtained, the determination of resistance through load tests is the most efficient method for the design of driven piles.

It is recommendable to evaluate the precision and efficiency of the resistance prediction methods, by analyzing the values of the coefficient of variation COV_R and the efficiency factor ϕ/λ_R, instead of using the values of resistance factors, since the latter are subject to small "traps", for example, the fact that the bias are higher suggests a higher resistance factor, although it does not necessarily imply that the method is more efficient.

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