



# Reliability-Based Calibration of Resistance Factors in LRFD Method for Driven Pile Foundations on Inshore Regions of Iran

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## Abstract

This paper presents the improvement of load and resistance factor design (LRFD) method for axially loaded driven piles in Iran. The LRFD method has been well developed and successfully implemented in geotechnical engineering, especially in the design of pile foundations in different parts of the world. To extend the use of this method in Iran, it is necessary to use the results of reliable local pile load tests and construction records to calibrate LRFD resistance factors regionally. To this end, we first collected a comprehensive database of static and dynamic load tests which have been performed on driven piles in fine-grained soils across Iran. Based on this database, we calculated the resistance factors for different design methods using three different methods of reliability analysis (FORM, FOSM, and MCS) and for two levels of reliability ( $\beta_T = 2.33$  and 3). Finally, we used these calculations together with experience and engineering judgment to propose resistance factors for the National Building Code of Iran.

**Keywords** LRFD · Code calibration · Reliability analysis · Pile foundation design

## Abbreviations

AASHTO	American Association of State Highway and Transportation Officials	DOT	Department of Transportation
ASD	Allowable stress design	DLT	Dynamic load test
AD	Anderson and Darling method	EOD	End of initial driving
BOR	Beginning of restrike	ENR	Engineering News Record
CAPWAP	Case Pile Wave Analysis Program	FORM	First-order reliability method
COV	Coefficient of variation	FOSM	First-order second moment
CPT	Cone penetration test	FS	Factors of safety
CHBDC	Canadian Highway Bridge Design Code	FHWA	Federal Highway Administration
DL	Dead load	GRLWEAP	Goble Rausche Likins wave equation analysis of piles
		LSD	Limit state design
		LRFD	Load resistance factor design
		LL	Live load
		MCS	Monte Carlo simulation
		NCHRP	National Cooperative Highway Research Program
		NBCC	National Building Code of Canada
		PDA	Pile driving analyzer
		SLT	Static load test
		SPT	Standard penetration test
		WSDOT	Washington State Department of Transportation

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## List of Symbols

$R^2$	Regression coefficient
$COV_R$	Coefficients of variation of resistance
$COV_{Q_L}$	Coefficients of variation of live load

$COV_{Q_D}$	Coefficients of variation of dead load
$\beta_T$	Target reliability index
$\lambda_R$	Resistance bias factor
$\lambda_D$	Dead load bias factor
$\lambda_L$	Live load bias factor
$\gamma_D$	Dead load factor
$\gamma_L$	Live load factor
$Q_D/Q_L$	Dead load to live load ratio
$\phi$	Resistance factor
$p_f$	Probability of failure
$A^2$	Test statistic for Anderson and Darling method
$\alpha$	Significance level
$\phi/\lambda_R$	Efficiency factor

## 1 Introduction

One of the most challenging issues in the geotechnical field is determination of the bearing capacity of pile foundations and many researchers have tried to improve this process [1–4]. In recent decades, structural design methodologies in many countries such as the USA, Canada, and European nations have changed from the allowable strength design (ASD) to the limit state design method, which is recently known as load and resistance factor design (LRFD) method [5]. In contrast to the ASD method in which only a global safety factor is proposed for evaluating the stability of the structure based on long-term engineering practice and experience, the LRFD method distinguishes the load and resistance factors. These factors take into account the inherent uncertainties in the prediction of the allowable loads including the estimation and measurement errors of the resistance and the load. The LRFD method uses the probability of failure or reliability to create a consistent safety zone in the design of the structures. The method is well established and used in structural engineering, which has led to constructive results. However, this method is still under development in certain areas of geotechnical engineering. In the past two decades, many attempts have been made to develop the LRFD method in foundation engineering [5].

Phoon [6] presented a reliability-based design method for the foundations of transmission line structures. Kim [7] calibrated the resistance factors of the LRFD method for driven pile foundations in North Carolina. Rahman [8] used the static and dynamic load test (DLT) results to expand the resistance factors for pile foundations in the design of highway bridge projects. Honjo [9] used the first-order reliability method (FORM) to calculate the resistance factors for pile foundations and showed that these factors depend on the type of the resistance distribution function and the uncertainties of soil parameters. Paikowsky [10] presented the calibration of resistance factors for pile foundations

using a complete database of different types of piles and soils, the results of which have been published as NCHRP Report 507 and have become a basis for the 2007 AASHTO bridge design specification. Allen [11] studied the history of the LRFD method's application and strongly recommended this method by enumerating its benefits. Furthermore, he provided a methodology for calculating resistance factors, which later became a basis for the 2010 AASHTO bridge design specification [12]. In 2012, a comprehensive research was carried out on the results of the tests conducted on the piles of a region in Iowa DOT. Based on this research and by using the reliability method, calibrated resistance factors for that area were presented. Kim [13] presented shaft and base resistance factors for drilled shaft embedded in rock based on a database in Korea. The method is still developing and expanding in different parts of the world, which has led to the development of several codes such as Eurocode 7 in Europe [14], highway structure foundations [10, 15, 16], transmission line structure foundations [17, 18] in the USA, limit state design (LSD) codes [19, 20], National Building Code [21] and Highway Bridge Design Code [22] in Canada, Building Code of Australia [23] and the Geo-Code 21 [9, 24] in Japan.

The latest edition of the Building Regulations of Iran (Part 7 of the National Building Code [25]) suggests using the LRFD method. Further, a simple table has been provided there which proposes the resistance factors for different ultimate load determination methods such as static analyses, direct in situ tests, DLT or static load test (SLT). Nevertheless, since these factors have been proposed mostly based on the local experience, engineering judgment, and fitting to the codes of other countries, they are not used in practice and the design of the piles is still carried out using the ASD method due to its widespread acceptability and the tendency of designers. To increase the acceptability of the LRFD method and encourage the engineers to use it, the calibration of resistance factors should be carried out using different reliability analyses and based on a comprehensive database of pile load tests.

The overall objective of this study is to improve the LRFD method by local calibration of resistance factors for axially loaded driven piles in Iran. The rest of the paper is organized as follows. Section 2 presents the information about the collected database on driven piles from various regions of Iran. In Sect. 3, we calculate the pile bearing capacity from different prediction methods such as static analysis methods, direct in situ test methods (SPT and CPT) and dynamic formulas, and present the results of their statistical analyses in Sect. 4. The calibration of resistance factors using different methods of reliability analysis and based on the collected data is presented in Sects. 5–9. In Sect. 10, we propose new resistance factors for the National Building

Code of Iran. Finally, Sect. 11 concludes and summarizes the results of this paper.

## 2 Development of Pile Load Test Database

As pointed out by Paikowsky [10] and Abu-Hejleh [26], the calibration of resistance factors based on the reliability method requires a high-quality database that includes important information on the pile, such as site conditions, pile specifications, method of execution, geotechnical characteristics of the site, and the results of the tests performed on the pile. The main criterion for adding a pile to our database was that the results of the static or dynamic tests should be available for this pile. We created a database which consists of 241 piles along with the results of static or dynamic tests and geotechnical tests of the site from various regions of Iran. Then, we categorized our database according to the pile and soil types and based on the contribution of each soil type to the overall pile bearing capacity. In our database, we had the following three pile types: square concrete piles, concrete spun piles, or steel pipe piles. If more than 70% of a pile capacity is from the contribution of cohesive soil layers, this pile will be put into the group of cohesive (fine-grained or clay) soils. If more than 70% of the pile capacity results from the contribution of non-cohesive materials, this pile will be assigned to the group of non-cohesive soils (coarse-grained soils or sand). If a pile does not belong to any of the above groups, it will be placed in the group of mixed soils. Based on the above classification which is shown in Table 1, for our collected data the soils fell mainly into the cohesive and mixed soil groups.

## 3 Pile Analysis Methods

The ultimate load of the piles can be predicted using (1) static analysis methods based on the soil properties; (2) the proposed relationships from in situ tests, which is also known as direct methods; (3) dynamic analysis based on dynamic formulas; (4) DLT; and (5) SLT [27]. For the static analysis methods, since most of the studied soils in the database are cohesive,

**Table 1** Classification of database contents according to the pile and soil types

Pile type	Cohesive soils	Non-cohesive soils	Mixed soils
Square concrete pile	102	N/A	N/A
Concrete spun piles	94	N/A	N/A
Steel pipe pile	5	N/A	29

NA not available

the  $\alpha$ -API method [28] and  $\beta$ -method [29] are employed. Four different CPT-based methods, including the French method or LCPC [30], Eslami and Fellenius method [31, 32], Schmertmann method [33], and Dutch method [34] and, further, three different SPT methods proposed by Schmertmann [35], Decourt method [36], and Shioi and Fukui method [37] are selected as direct methods. For dynamic analysis, the Engineering News Record (ENR) formula [38], Gates formula [39], FHWA Modified Gates formula [40] and The Washington State Department of Transportation (WSDOT) formula [41] are implemented for predicting the pile capacity. The tip and shaft resistances from DLT using pile driving analyzer (PDA) equipment are estimated using the Case Pile Wave Analysis Program (CAPWAP) method [42] at the end-of-drive (EOD) and beginning of restrrike (BOR). For SLT results, Davisson Offset Limit Criterion [43] is selected for determining the pile ultimate load. The details of the collected data and the methods used for the analysis of the data are presented in Table 2.

## 4 Analysis of Data

The prediction methods for pile ultimate loads employed in this study include static analysis methods, direct in situ test methods, dynamic formulas, and DLTs. To evaluate the performance of these prediction methods, the estimated capacities are compared with the capacities measured with the SLT. SLT serves as a benchmark for performance evaluation of the other predicting methods, because it is globally well accepted that SLT accurately measures the ultimate load of the pile. As performing SLT is time consuming and the costs are often difficult to justify for ordinary or small constructions, the number of tests available in various projects across the country (except for large industrial projects) is currently limited. On the other hand, the DLT has gained remarkable attention globally, specifically in Iran as pointed out by many researchers (e.g., [44–47]). The regression analysis is carried out on the available data to compare the results of DLT at BOR condition and the results of SLT. The comparison of the results for DLT and SLT is shown in Fig. 1. This figure indicates a very good correlation between the two tests with a relatively high regression coefficient ( $R^2$ ). This is an indication that the results of DLT at BOR condition (hereafter DLT-BOR) can be considered as the measured ultimate load of the piles and, hence, can be used in the comparisons of this study.

## 5 Calibration of Resistance Factors

### 5.1 Calibration Using Reliability Theory

Generally, the calibration of the resistance factors of the LRFD method is performed using one of the following

**Table 2** Summary of the collected database for calibration of resistance factors

Project site name	Pile type	Soil type	Total cases	Static load test	Dynamic load test			Dynamic formulas					Calculated static pile capacity				
					test			EOD	BOR	ENR	FHWA Gates	Gate	WSDOT	CPT	SPT	$\alpha$ -API	$\beta$ -Method
					EOD	BOR	ENR										
Bu Ali Sina	Concrete pile	C	10	–	1	10	10	10	10	10	10	–	–	–	10	10	
Abadan	Concrete pile	C	2	2	–	–	–	–	–	–	–	–	–	–	–	–	
Bandar Imam	Concrete pile	C	3	–	3	3	3	3	3	3	3	–	–	–	–	–	
Folad Jahan Ara	Concrete pile	C	61	6	2	59	56	56	56	56	56	29	60	60	60	60	
Fajr II	Concrete pile	C	12	5	12	10	6	6	6	6	6	–	8	–	–	–	
North Azadegan Oilfield	Concrete pile	C	14	4	14	14	14	14	14	14	3	12	14	14	14	14	
Bandar Imam-II	Concrete pile	C	41	3	–	41	39	39	39	39	–	–	–	–	–	–	
Folad Shadegan	Concrete pile	C	12	3	12	9	9	9	9	9	–	12	9	9	9	9	
Shekar Novin	Concrete pile	C	13	–	11	13	12	12	12	12	2	8	7	–	–	–	
Kaveh	Steel pipe	C	5	–	–	5	5	5	5	5	–	–	–	–	–	–	
Bidboland II	Concrete pile	C	28	3	28	28	28	28	28	28	–	27	28	28	28	28	
Pars Jonobi	Steel pipe	M	24	2	3	21	22	22	22	22	–	–	–	–	–	–	
Karun	Steel pipe	M	5	–	5	5	5	5	5	5	–	–	–	–	–	–	
Chabahar	Steel pipe	L	4	–	4	–	4	4	4	4	–	–	–	–	–	–	
Bandar Kangan	Steel pipe	L	7	–	–	7	–	–	–	–	–	–	–	–	–	–	
Total			241	28	95	225	213	213	213	220	213	34	132	131	121	121	

C cohesive soil, M mix soil, L limited data

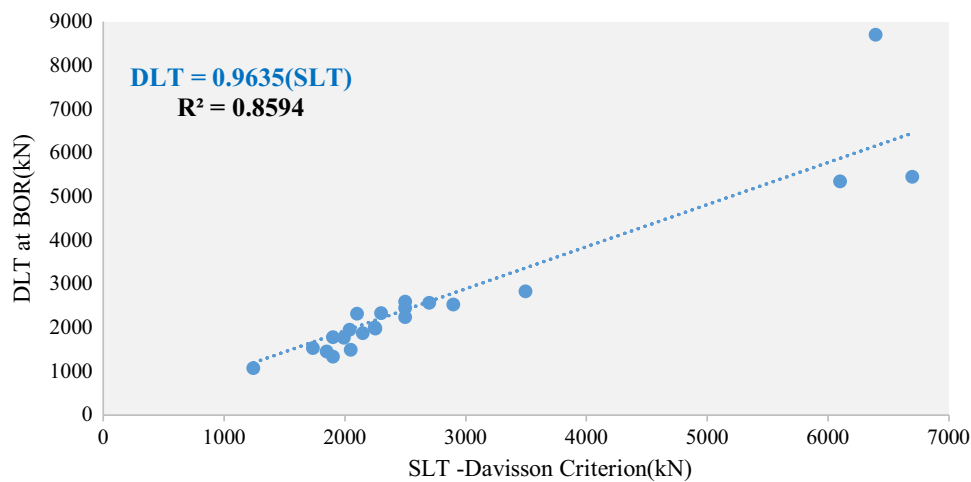


Fig. 1 Comparison of SLT and DLT-BOR tests based on the database

methods: (1) incorporating experience and engineering judgment as well as recommendations in design codes, (2) reliability analysis and probability theory, and (3) combination of the above two methods. In this paper, the reliability analysis combined with experience and engineering judgment is employed to determine the resistance factors.

Calibration using reliability theory consists of limiting the probability of failure ( $p_f$ ) of structures or the reliability index to a certain acceptable level. Barker [48] suggested first-order second moment (FOSM) to calibrate the resistance factor. Paikowsky [10] compared the results of FOSM with FORM, which is more precise compared to FOSM, and showed that the coefficients obtained by FOSM are approximately 10% less than the results obtained by FORM. Furthermore, Allen [11] showed that the results of the Monte Carlo simulation (MCS) are 10–20% higher than the results of FOSM. Equation (1) expresses the use of FOSM to calibrate the resistance factor as suggested by Barker [48],

$$\phi = \frac{\lambda_R \left( \frac{\gamma_D Q_D}{Q_L} + \gamma_L \right) \sqrt{\frac{1 + \text{COV}_{Q_D}^2 + \text{COV}_{Q_L}^2}{1 + \text{COV}_R^2}}}{\left( \frac{\lambda_{Q_D} Q_D}{Q_L} + \lambda_{Q_L} \right) \exp \left\{ \beta_T \sqrt{\text{Ln} \left( (1 + \text{COV}_R^2) \left( 1 + \text{COV}_{Q_D}^2 + \text{COV}_{Q_L}^2 \right) \right)} \right\}}, \tag{1}$$

where  $\text{COV}_R, \text{COV}_{Q_L}, \text{COV}_{Q_D}$  are coefficients of variation of “resistance”, “live”, and “dead” loads, respectively;  $\beta_T$  is target reliability index;  $\lambda_R$  is resistance bias factor (ratio of the measured value to the predicted value for the resistance);  $\lambda_D$  and  $\lambda_L$  are dead and live load bias factors, respectively;  $\gamma_D$  and  $\gamma_L$  are the dead and live load factors, respectively; and  $Q_D/Q_L$  is the dead load to the live load ratio. According to Eq. (1), two sets of data are required for reliability analysis on the pile foundations: (1) load information that includes

load factors and the statistics of load bias factors, and (2) resistance information that includes the statistics of resistance bias factors.

### 5.2 Load Factors and Uncertainties of the Loads

In this study, two types of axial loads have been considered on a pile: (1) dead load (DL) and (2) live load (LL). According to the National Building Codes of Iran, the load factors of DL and LL for the building structures are 1.2 and 1.5, respectively. The uncertainties of DL and LL for the building structures are summarized in Table 3. The uncertainties of the loads include specifying bias factor ( $\lambda$ ), coefficients of variation (COV), and distribution types. In this analysis, the values of bias factor and COVs in Table 3 are used to simulate the uncertainties of DL and LL for the building structures.

Table 3 Bias factor, coefficients of variation, and distribution type of DL and LL for building structures [50]

Load type	Bias factor ( $\lambda$ )	Coefficient of variation (COV)	Distribution type
DL	1.05	0.10	Normal
LL	1.0	0.25	Type I based on largest extreme

Nowak [16] stated that dead and live loads follow a normal distribution. Scott and Salgado [49] stated that the distribution of transient loads is closer to the log-normal distribution and can be modeled with their first two moments. They also showed that since the magnitude of the transient loads and the resistance in geotechnical problems is positive, the log-normal distribution can better model these variables. Furthermore, it should be noted that since COV values are usually small for the loads and large for the resistance, the distribution type for the resistance and the load variables would not have much effect on the final calibration results. Consequently, we assume the log-normal distribution for both the dead and live loads.

In NCHRP 507, Paikowsky [10] suggested that for the pile foundations the ratio of the dead load to the live load (DL/LL ratio) should be between 2 and 2.5. Allen [11] used a more conservative value of 3 for this ratio. Nowak [16] and Paikowsky [10] analyzed the various DL/LL ratios and showed that the value of this ratio would not have much influence on the calibration results of the resistance factors. Consequently, we consider a DL/LL ratio of 3 in this study.

According to Barker [48], the range of target reliability index ( $\beta_T$ ) for designing the pile foundations is between 2.5 and 3. For axially loaded piles, Paikowsky [10] recommended target reliability indices of 2.33 (corresponding to 1% probability of failure) for redundant pile groups and 3.00 (corresponding to 0.1% probability of failure) for non-redundant pile groups. In this research, we calculate the resistance factor for both the target reliability indices of 2.33 and 3.

### 5.3 Statistics of Resistance Bias Factors

As stated in the previous sections, the results of the DLT at BOR (DLT-BOR) are considered as the measured values for the ultimate load and are compared with the predicted values. In Eq. (1), it is supposed that the resistance follows a log-normal distribution. To verify this assumption, we used a hypothesis test based on the normality method proposed by Anderson and Darling [51] to assess the goodness of fit for the assumed distributions. The Anderson–Darling (AD) method was selected because it is appropriate for small sample sizes [52]. The hypothesis regarding the distributional form is rejected at the chosen significance level ( $\alpha$ ) if the “test statistic” ( $A^2$ ) is greater than the critical value. The critical value for  $\alpha=0.05$  is equal to 2.50. The results of the goodness of fit of the AD test are shown in Fig. 2 and Table 4.

## 6 Computation of the LRFD Resistance Factors

Based on the load and resistance information mentioned in the previous section, we utilize FOSM and MCS to determine the resistance factors based on ultimate limit state

at target reliability indices of 2.33 and 3.00 (corresponding to the probabilities of failure equal to 1.0% and 0.1%, respectively). Resistance factor calibration for these methods (FOSM, MCS) is performed using a code written in MATLAB. Since a higher resistance factor does not necessarily imply an efficient pile analysis method, an efficiency factor was utilized to effectively compare the reliability performance of the pile analysis methods. As stated by McVay [53], the efficiency factor ( $\phi/\bar{\lambda}_R$ ) is essentially the resistance factor divided by the mean of resistance bias factor for the particular pile analysis method. A better pile analysis method would have a higher efficiency factor, thus reducing the number of piles required to support the design load [53]. An equivalent factor of safety (FS) can be calculated based on FOSM and the relationship is provided by Barker [48]:

$$FS = \frac{\gamma_D Q_D + \gamma_L}{\phi \left( \frac{Q_D}{Q_L} + 1 \right)} \quad (2)$$

Based on the equivalent FS, Paikowsky proposed in [10], actual safety factor which can be calculated by multiplying FS and the mean of resistance bias factor ( $FS \times \bar{\lambda}_R$ ). Table 5 shows the results of resistance factor calibration for different predicted methods. The efficiency factor ( $\phi/\bar{\lambda}_R$ ), equivalent FS, and actual safety factor ( $FS \times \bar{\lambda}_R$ ) presented in Table 5 are calculated based on MCS resistance factor.

## 7 Evaluation of Calibration Results

Based on the efficiency factors ( $\phi/\bar{\lambda}_R$ ) and other calibration statistics presented in Table 5, DLT-BOR has a better performance compared to all other methods with an efficiency factor of about 0.77 ( $\beta_T=2.33$ , MCS). This value for the efficiency factor indicates that by using DLT-BOR, about 77% of the long-term capacity was achieved. This relatively good efficiency factor is attributed to the good accuracy of the method which is described by a mean of resistance bias factor of 1.15 and a good precision corresponding to a COV of 0.18.

The good precision of DLT-BOR is also verified by a large resistance factor ( $\phi$ ) (0.89 for  $\beta_T=2.33$ , MCS). However, in the DLT-EOD method, because of the large bias factor (underpredicted method) and large COV (dissipation of result), the values for the resistance factor are large (close to DLT-BOR state), while such quantities do not seem reasonable in terms of engineering judgment. Since most of the cases collected in this study are piles embedded in fine-grained clayey soil, the effect of soil setup on the final capacity is very significant and influential. Therefore, the reduction factor based on DLT-EOD results regardless of

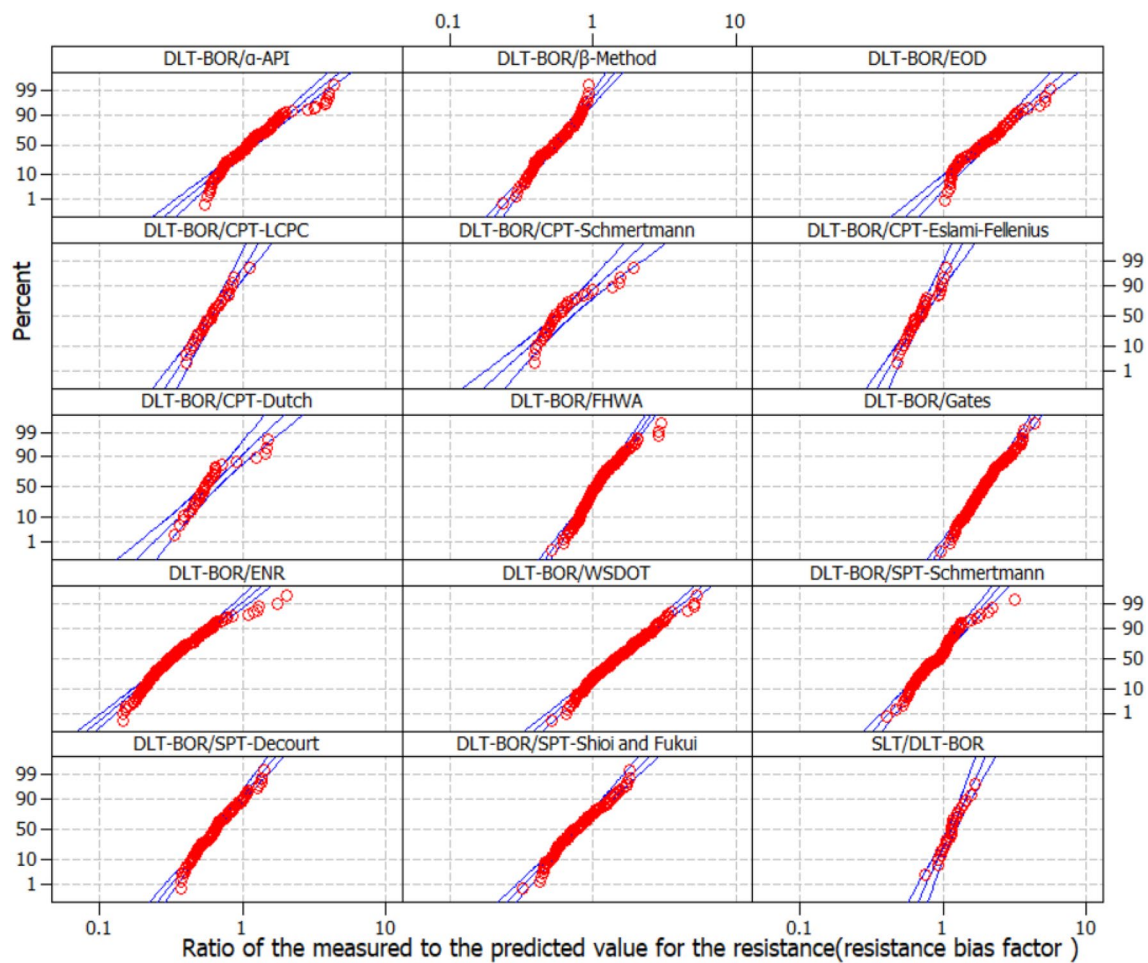


Fig. 2 Results of the goodness of fit of Anderson–Darling (AD) test for log-normal distribution

Table 4 Results of the goodness of fit of Anderson–Darling (AD) test for resistance bias factors

Measured method	Predicted method	Mean of bias factor ( $\lambda_R$ )	Standard deviation	No. of data	AD test statistic for distribution	
					Log-normal	Normal
DLT-BOR	$\alpha$ -API	1.30	0.77	130	1.69	9.52
	$\beta$ -Method	0.56	0.17	120	0.89	1.47
	FHWA Gate formula	1.13	0.36	203	2.00	7.85
	Gate formula	2.00	0.58	210	0.72	4.14
	ENR formula	0.37	0.24	203	2.02	15.33
	WSDOT formula	1.66	0.81	203	0.47	5.76
	SPT-Schmertmann	0.94	0.36	121	0.85	3.81
	SPT-Decourt	0.68	0.22	123	0.51	2.72
	SPT-Shioi and Fukui	0.83	0.33	123	0.71	3.45
	CPT-LCPC	0.63	0.16	33	0.20	0.51
	CPT-Dutch	0.64	0.31	33	1.80	4.00
	CPT-Eslami–Fellenius	0.70	0.16	33	0.59	1.09
	CPT-Schmertmann	0.69	0.37	33	1.61	3.55
	DLT-EOD	2.10	0.98	80	0.78	2.68
SLT	DLT-BOR	1.15	0.21	26	0.35	0.50

**Table 5** Statistics for calibration of resistance factors based on reliability theory with reference to measured ultimate load by SLT and DLT-BOR

Measured method	Predicted method	$\bar{\lambda}_R$	COV <sub>R</sub>	No. of data	$\beta_T=3.00$					$\beta_T=2.33$				
					$\phi^a$	$\phi^b$	$\frac{\phi}{\lambda_R}$	FS	FS $\times \bar{\lambda}_R$	$\phi^a$	$\phi^b$	$\frac{\phi}{\lambda_R}$	FS	FS $\times \bar{\lambda}_R$
DLT-BOR	$\alpha$ -API	1.30	0.59	130	0.24	0.26	0.20	5.05	6.56	0.36	0.39	0.30	3.37	4.38
	$\beta$ -Method	0.56	0.31	120	0.21	0.26	0.46	5.05	2.83	0.28	0.33	0.59	3.98	2.23
	FHWA Gate formula	1.13	0.32	203	0.41	0.50	0.44	2.63	2.96	0.54	0.64	0.56	2.07	2.33
	Gate formula	2.00	0.29	210	0.79	0.98	0.49	1.34	2.68	1.02	1.20	0.60	1.09	2.19
	ENR formula	0.37	0.64	203	0.06	0.07	0.17	20.19	7.55	0.09	0.10	0.27	13.13	4.91
	WSDOT formula	1.66	0.49	203	0.40	0.45	0.27	2.92	4.83	0.57	0.63	0.38	2.10	3.48
	SPT-Schmertmann	0.94	0.38	121	0.29	0.35	0.37	3.80	3.58	0.40	0.46	0.49	2.85	2.68
	SPT-Decourt	0.68	0.33	123	0.24	0.30	0.44	4.38	2.97	0.32	0.38	0.56	3.45	2.35
	SPT-Shioi and Fukui	0.83	0.39	123	0.25	0.30	0.36	4.38	3.64	0.35	0.40	0.47	3.32	2.77
	CPT-LCPC	0.63	0.25	34	0.27	0.35	0.56	3.75	2.36	0.34	0.43	0.68	3.05	1.92
	CPT-Dutch	0.64	0.49	34	0.15	0.17	0.27	7.72	4.94	0.22	0.24	0.38	5.47	3.50
	CPT-Eslami–Fellenius	0.70	0.23	34	0.31	0.41	0.59	3.20	2.24	0.40	0.49	0.70	2.68	1.88
	CPT-Schmertmann	0.69	0.53	34	0.15	0.17	0.25	7.72	5.33	0.21	0.24	0.35	5.47	3.77
	DLT-EOD	2.10	0.46	80	0.53	0.61	0.29	2.17	4.56	0.75	0.84	0.40	1.56	3.28
SLT	DLT-BOR	1.15	0.18	26	0.57	0.77	0.67	1.70	1.96	0.71	0.89	0.77	1.47	1.70

<sup>a</sup>Resistance factor based on FOSM

<sup>b</sup>Resistance factor based on MCS

the soil setup effect is not recommended for the purposes of pile capacity prediction.

The static analysis methods using  $\alpha$ -API and  $\beta$ -method have shown a resistance factor of about 0.39 and 0.33 ( $\beta_T=2.33$ , MCS) and an efficiency factor of 0.30 and 0.59, respectively. The performance of the static analysis methods is greatly influenced by the type of correlations used to interpret the soil properties, the soil/test conditions based on which the method is proposed, and the theoretical framework to which the methods are attributed. For example, poor correlations to determine soil strength properties (such as converting SPT-N values to shear strength parameters) can produce poor and erratic predictions of the pile capacity.

In dynamic formula methods, it is observed that FHWA Gate and Gate methods have resulted in better efficiency factors (0.56 and 0.60) compared to the other methods, while the resistance factors for these methods are equal to 0.64 and 1.20 (for  $\beta_T=2.33$ , MCS). For the fine-grained soils, since the value of bearing capacity in BOR state is around 1.5–5 times larger than the corresponding capacity in EOD condition, the driving records of the pile at BOR state are used to calculate the dynamic formulas.

Conceptually, dynamic formulas can be used for pile ultimate load estimation. Many relations have been proposed in literature to establish correlations between pile penetration rate during driving and its ultimate capacity. However, dynamic formulas are rarely used nowadays as they are not accurate in ultimate load predictions due to insufficient theoretical basis in their development. The main assumption in

derivation of all dynamic formulas is that the pile shaft is rigid and the hammer ram impact on the pile head is sensed at the pile tip instantly, which is of course not correct. To overcome this significant shortcoming, stress wave theories emerged where wave propagation of axial stress in the shaft due to the dynamic impact on the pile head is considered. Therefore, the calculated values of the resistance factors based on dynamic formulas are not recommended for the initial design of the piles.

Based on the results presented in Table 5 for SPT methods, Decourt method has shown a larger efficiency factor (0.56 for  $\beta_T=2.33$ , MCS). However, the results show that the obtained resistance factors are almost the same regardless of the method used to evaluate the ultimate load. For CPT methods, Eslami–Fellenius and LCPC have shown larger efficiency factors (0.70 and 0.68, respectively, for  $\beta_T=2.33$ , MCS) compared to the other methods. Fakharian [54] also showed that Eslami–Fellenius method more accurately predicts the bearing capacity of piles at BOR condition for the clayey soils.

## 8 Resistance Factors for Pile Static Load Tests

To calculate the resistance factor based on the SLT result, the value of resistance bias factor and COV needs to be specified first. Since the resistance bias factor is the ratio of the measured value by SLT to the predicted value, this ratio is



equal to one for SLT. Spatial variations in every site from one pile to another are reflected by the value of COV. As there is not usually sufficient quantity of reliable data to estimate COV at a site, it is possible to arbitrarily divide the sites into three categories of “low”, “medium”, or “high” variability and associate COVs of 0.15, 0.25, and 0.35 to these three categories, respectively [55]. Benjamin and Cornell [56] showed that by increasing the number of SLTs at a site, the COV is reduced by a ratio of  $1/\sqrt{n}$ , where  $n$  is the number of tested piles. As a result, the resistance factor as a function of the site variability, the number of piles tested, and the target reliability are presented in Table 6. However, based on the engineering judgment and worldwide experiences, it is recommended that the resistance factor for SLT should not be greater than 0.85 for  $\beta_T=2.33$  and 0.75 for  $\beta_T=3.0$ .

( $COV_R$ ) is performed. To this end, using FOSM method and for  $\beta_T=2.33$ , the resistance factors for different values of  $\lambda_R$ ,  $COV_R$  are calculated and the results are shown in Fig. 3. This figure shows that:

1. As  $COV_R$  increases, the resistance factor decreases.
2. Resistance factor in the underpredicted methods ( $\lambda_R > 1$ ) is very sensitive to variations in  $COV_R$ . While in the overpredicted methods ( $\lambda_R < 1$ ), the resistance factor changes marginally with increase in  $COV_R$ .
3. For a given value of  $COV_R$ , the resistance factor increases by increase in  $\lambda_R$ . This means that the underpredicted methods show a higher value of resistance factor and overpredicted methods show a lower resistance factor.

### 9 Sensitivity Analysis for Resistance Bias Factor ( $\lambda_R$ ) and COV of Resistance ( $COV_R$ )

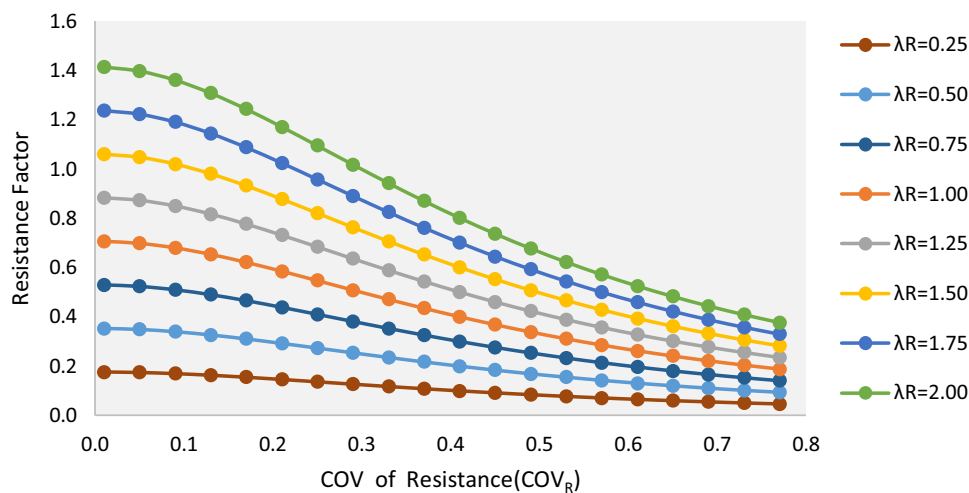
To better understand the process of calculating resistance factors using reliability analysis, sensitivity analysis for values of the resistance bias factor ( $\lambda_R$ ) and COV of resistance

### 10 Recommended Resistance Factors for Iran Code

Recommending resistance factors for incorporating into the National Building Code of Iran is a complicated process. In some instances, this process cannot simply be performed

**Table 6** The resistance factors for the number of SLTs conducted per site

Number of load tests	$\beta_T=3.0$			$\beta_T=2.33$			
	Low	Medium	High	Low	Medium	High	High
1	0.73	0.55	0.41	0.83	0.67	0.53	
2	0.80	0.67	0.55	0.90	0.78	0.67	
3	0.84	0.75	0.63	0.93	0.85	0.75	
4	0.86	0.77	0.67	0.95	0.87	0.78	



**Fig. 3** Resistance factors for different values of  $\lambda_R$   $COV_R$

**Table 7** Recommended resistance factors for Iran National Building Code (driven piles in clay)

Pile analysis method	Method	Recommended resistance factor		Current resistance factor in Iran National Building Code (2013)	CHBDC (2006)	NBCC (2010)
		$\beta_T=3.00$	$\beta_T=2.33$			
In situ test	CPT method	0.40	0.50	0.50	–	0.40
	SPT method	0.30	0.40	–	–	–
Static analysis	$\beta$ Method	0.25	0.35	0.35	0.40	–
Dynamic formulas <sup>a</sup>	FHWA Gate	0.50	0.60	–	0.40	–
Dynamic load test (CAPWAP)	EOD <sup>a</sup>	0.55	0.70	–	–	–
	BOR	0.65	0.75	0.55	0.50	0.50
Static load test	Davisson offset	As in Table 6		0.65	0.60	0.60

<sup>a</sup>Not recommended for design (only for construction control)

based on the reliability analysis results, and experience and engineering judgment also need to be employed to obtain meaningful results. Based on the factors obtained from different pile design methods and discussions of Sect. 6 and for driven piles in fine-grained, the proposed resistance factors for the National Building Code of Iran are shown in Table 7. For the purpose of comparison, the magnitudes of resistance factors in the current issue of the National Building Code of Iran are also presented in Table 7.

We believe that the methods which considerably overpredict or underpredict should be eliminated from the cycle of design because they generate unrealistic values for the resistance factors. In addition, methods with large COV are not recommended to predict the ultimate load in the design process. It is necessary to point out that since the soil type in the collected data is generally fine-grained, the proposed resistance factors are only applicable for this type of soil. Table 7 shows the comparison of our recommended resistance factors with the resistance factors of two widely used Canadian codes, i.e., the National Building Code of Canada (NBCC) [57] and the Canadian Highway Bridge Design Code (CHBDC) [58].

## 11 Conclusions

In this study, we first created a database from several industrial construction sites across Iran. Our criterion for including a data in our database was that extensive pile construction monitoring information and load test results (static/dynamic load tests) should be available for this data. Then, we processed and analyzed the information available in this database and used it to calculate the resistance factors for different design methods using three different methods of reliability analysis (FORM, FOSM, and MCS) and for two levels of reliability ( $\beta_T=2.33$  and 3). Finally, we used these calculations together with experience and engineering judgment to propose resistance factors for National Building

Code of Iran. Since these new factors have been proposed using different reliability analyses, the engineers can use them more confidently and reliably.

The most important findings of the study are summarized below:

1. Based on the results obtained primarily from static analysis methods and statistical analyses,  $\beta$ -method is recommended for the design of driven piles in the fine-grained soil. Our proposed resistance factor for this method ( $\beta_T=2.33$ ) is equal to its current value in the National Building Code of Iran. Therefore, the current value of the code for this method seems reasonable.
2. To the best of our knowledge, our paper is the first one that uses the results of three different SPT methods in the fine-grained soil to calculate the resistance factors. The results have shown that the obtained resistance factors are almost the same regardless of the type of SPT methods used to evaluate the ultimate load.
3. Based on the results of the four different CPT methods, Eslami–Fellenius and LCPC methods showed larger efficiency factors and, hence, they are recommended for predicting the bearing capacity of driven piles in the fine-grained soil. The suggested resistance factor for this method ( $\beta_T=2.33$ ) is equal to its current value in the National Building Code of Iran.
4. Based on the results obtained for the dynamic formulas, the FHWA Modified Gates and Gate formula showed the best efficiency factor. These methods can be simply used in the construction control of driven pile foundations in the clayey soils, but they are not recommended for capacity prediction in the design process.
5. Based on the efficiency factor of different pile design methods, the DLT at the BOR is shown to have the best performance in the pile capacity prediction and is recommended for the design of the driven piles in the fine-grained soil. Furthermore, because of the large bias factor (underpredicted method) and large COV (dissipa-

tion of result), the DLT-EOD method is only recommended for construction control of driven piles in the fine-grained soil. The wide range of the proposed resistance factors in the codes and handbooks can be possibly attributed to ambiguities in using one of the EOD or BOD for the DLT data.

6. For the SLT method, the resistance factor is presented as a function of the site variability, the number of piles tested, and the levels of reliability. This function makes the process of finding the resistance factor easier and safer.

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