Research Article

Bayesian Estimation of Resistance Factor for Bored Piles Based on Load Test Database

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The quality of in situ data is key to calculating resistance factor of bored piles. However, it is difficult to summarize accuracy data due to various uncertainties in engineering. This paper employs the Bayesian method and mathematical statistics theory to put forward an estimation method for updating in situ data. A testing database (33 tests in noncohesive soils and 53 tests in cohesive soils) of bored piles is summarized. The model factor of bored piles is quantified as the ratio of the measured capacity to the calculated capacity. The proposed method is used to classify summarized data into three categories, which are “good data,” “general data,” and “bad data.” The “bad data” are discarded because of bad contribution to calculation, and Bayesian theory is incorporated into updating the model factor statistics. Three methods are used to calculate the reliability index and resistance factor of bored piles, and the results show that the reliability index and resistance factor are sensitive to the quality of data. Finally, the available values of resistance factors are proposed based on resistance factor design for bridge design specification, which can offer references to revision relevant specifications. The proposed method can be used to update other geotechnical data.

1. Introduction

Bored piles, especially large-diameter piles, are commonly employed to support high-rise buildings and bridges in China and other countries because of their ability to sustain large load [1–5]. The safety of bored pile foundation is significantly important. Due to various uncertainties, the design parameters should have random variances. However, design parameters are described as constants by allowable stress design (ASD) philosophy, which is unreasonable and unscientific. To overcome the deficiencies, load resistance factor design (LRFD) method is mandated by American Association of State Highway and Transportation Officials [6]. Therefore, resistance factor calculation of bored piles is of engineering significance.

The resistance factor is calculated incorporating in reliability analysis methods based on pile load test data [7, 8]. Enough-accuracy in situ data are necessary to calculate resistance factor of bored piles. However, it is difficult to collect accuracy in situ data to calculate reliability index and resistance factor because of various uncertainties, for

example, parameter uncertainty, calculation model uncertainty, testing random error, and systematic error. A large number of investigations are carried out to calibrate resistance factor of driven piles [7–16], and significant achievements have been developed. However, few investigations about resistance factor of bored piles have been reported.

Parameter uncertainty and model uncertainty are two troubles for pile foundation designers. Numerous investigations are conducted to study parameter uncertainty, which shows that parameter uncertainty contains random error of monitor, system error, statistical uncertainty, and so on. Model uncertainty is mainly caused by simplified calculation model. European design specification of geotechnical engineering (EN997-1) clearly suggests that a model revised factor should be incorporated when the pile capacity is calculated using the simplification model [17]. However, this specification does not specify revised factor values and only suggests that different countries should adopt different values. Jones et al. [18], Kulhawy and Trutmann [19], Lacse and Nadim [20], Meyerhof [21], and Phoon and Kulhawy

[22, 23] study model uncertainty based on lots of in situ data of pile capacity, which shows that enough-accuracy data are necessary to solve model uncertainty problem. However, it is difficult to get enough-accuracy data due to various uncertainties. In addition, the quality of collected data is not all perfect, and some of them are considered as “bad data” or “data outliers.” It is necessary that data optimization is incorporated into calculating resistance factor of bored piles.

This paper puts forward a Bayesian estimation method to update the in situ data of bored piles, and three reliability index calculation methods are incorporated into calculating the reliability index of pile capacity using the processing data. Then American LRFD for Bridge Design Specification is used to estimate the resistance factor of bored piles.

2. Bayesian Optimization Method

Bayesian principle is a tool to update the probability distribution using new information. Assuming that the prior distribution of a random variable (X) is $f'_X(X)$, its posterior distribution can be written as [24]

$$f''_X(X) = K \cdot L(X) \cdot f'_X(X), \quad (1)$$

where $f''_X(X)$ is posterior distribution of X ; K is a normalization constant; and $L(X)$ is likelihood function. Normal distribution and log-normal distribution are frequently employed to fit probability distribution of pile capacity [25].

Assume that n values of X are collected from engineering, which are described as $X = (X_1, X_2, \dots, X_n)$. The mean (μ_p) and standard variance (σ_p) are

$$\mu_p = \frac{1}{n} \sum_{i=1}^n X_i, \quad (2)$$

$$\sigma_p = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \mu_x)^2}.$$

Assume that μ_K and σ_K are considered as the mean and standard variance of likelihood function. If X obeys normal distribution, the posterior mean (μ_U) and variance (σ_U) are

$$\mu_U = \frac{\mu_p \sigma_K^2 + \mu_K \sigma_p^2}{\sigma_p^2 + \sigma_K^2}, \quad (3)$$

$$\sigma_U^2 = \frac{\sigma_p^2 \sigma_K^2}{\sigma_p^2 + \sigma_K^2}. \quad (4)$$

If X obeys log-normal distribution, it can be translated into normal random variable through dealing X with natural logarithm, which is described as $\ln X$. The mean ($\mu_{\ln X}$) and standard variance ($\sigma_{\ln X}$) of $\ln X$ are

$$\mu_{\ln X} = \exp(\mu_U + 0.5\sigma_U^2), \quad (5)$$

$$\sigma_{\ln X}^2 = \mu_{\ln X} [\exp(\sigma_U^2) - 1]. \quad (6)$$

The model factor is frequently represented as the ratio of the measured capacity to calculated capacity [1, 7, 8]:

$$\lambda = \frac{Q_m}{Q_p}, \quad (7)$$

where λ is model factor of pile capacity; Q_m is the measured pile capacity; and Q_p is the calculated pile capacity. Numerous investigations show that model factor is a random variable and obeys log-normal distribution [1, 2, 7, 10, 13, 14].

To improve accuracy of collected data from engineering, this paper employs the biased factor of λ , which is shown in the following equation [26]:

$$\zeta_i = \frac{|\lambda_i - \lambda_R|}{\lambda_R}, \quad 1 \leq i \leq n, \quad (8)$$

where λ_i is the i th model factor; ζ_i is i th biased factor of λ ; and λ_R is the mean of λ .

Based on equation (8), the data are classified as follows [26]:

- (1) If $\zeta_i < 0.25$, the data are defined as “good data” because it is near to the fact data.
- (2) If $0.25 \leq \zeta_i < 0.5$, the data are defined as “general data.”
- (3) If $\zeta_i \geq 0.5$, the data are defined as “bad data.” “Bad data” are identified as extreme values, which should be discarded.

“Good data” are considered to be more reliable and should be treated as the prior information in estimation of the population statistics. However, the sample size of the “good data” is not sufficient to represent the total. This paper employs Bayesian updating technique to evaluate the probability characteristics of the resistance bias factor for bored piles. The “general data” are treated as prior information, and the “good data” are treated as likelihood information. Then, the updating model factor statistics can be obtained using equations (3)–(6).

3. Resistance Factor Estimation

This paper summarizes various bored pile capacity data shown in Tables 1 and 2 [1]. The data are divided into two groups, which are the data in noncohesive soil (D-NC) and the data in cohesive soil (D-C).

Dithinde et al. [1] use load-displacement curves (shown in Figure 1) to improve the quality of collected data. The characteristic of Case Numbers 25 curve is far away from other curves; it falsely needs to be discarded. In addition, Dithinde et al. [1] employ Box-Plots Method to detect that Case Number 24 and Case Number 26 are outliers. Therefore, Case Numbers 24, 25, and 26 should be discarded. Figure 2 shows the scatter diagram of the remaining data, which indicates that there are no data deviating markedly from other data. However, it does not mean that the remaining data are absolutely reliable. This paper will use the proposed method to update remaining data.

TABLE 1: Load testing data of pile capacity in noncohesive soil.

Case number	D_s (mm)	D_B (mm)	L (m)	s (mm)	Q_p (kN)	Q_m (kN)	a	b
1	430	430	8	0.42	1321	1375	0.06	0.99
2	600	750	9	0.76	3783	4600	0.74	0.94
3	750	600	11	1.2	2705	3000	0.40	0.97
4	360	350	7.8	35	1084	1050	7.98	0.61
5	400	400	9.5	5.6	1202	1357	1.40	0.89
6	400	400	9.5	10.1	1202	1380	1.45	0.92
7	400	400	8	6	1131	1050	0.80	0.92
8	400	400	9.5	5	1202	1225	1.97	0.84
9	400	400	3	11	1178	840	3.70	0.72
10	520	520	16.5	12.7	6754	5600	3.91	0.86
11	430	430	11.5	3.41	1287	1250	0.75	0.94
12	450	450	9	0.97	1145	1500	2.08	0.80
13	400	400	10	50	940	970	3.88	0.74
14	400	400	7	70	679	540	2.89	0.73
15	500	500	7.8	75	1226	600	10.93	0.46
16	500	500	10	77	1583	1175	5.29	0.59
17	400	400	11	41	605	800	5.92	0.72
18	400	400	9.2	57	472	480	7.87	0.58
19	500	500	9.5	60	793	625	8.13	0.44
20	500	500	11.8	62	1060	1025	10.46	0.51
21	500	500	12.3	60	916	1160	4.29	0.70
22	500	500	14.5	80	1132	1500	3.90	0.75
23	305	305	13	40.3	2028	2010	8.44	0.50
24	305	305	13	6.4	3051	6000	4.80	0.60
25	305	305	13	97	2028	1200	1.30	0.53
26	305	305	13	18.3	3051	4650	1.13	0.97
27	520	760	12.2	50	2563	1690	2.97	0.83
28	520	760	12.2	93	2478	1620	3.36	0.84
29	520	760	12	26.5	2111	1650	5.36	0.80
30	520	760	12	35	2451	2100	4.60	0.70
31	520	760	15	23.3	2974	2680	8.80	0.85
32	520	760	6	3.5	3644	3650	0.06	0.99
33	520	760	8	5	3739	5600	0.74	0.94

The classified results are shown in Tables 3 and 4. There are 21 and 38 pieces of data, of which bias factor is less than 0.25 in noncohesive soil and cohesive soil, respectively. The in situ uncertainties have little contribution to these data classified as “good data.” There are 8 and 12 pieces of data, of which bias factor is larger than 0.25 but less than 0.50 in noncohesive soil and cohesive soil, respectively, considered as “general data.” However, the bias factors of Case Number 15 in noncohesive soil and Cases Numbers 37, 68, and 69 in cohesive soil are 0.5187, 0.5271, 0.7315, and 0.5203, respectively. These data are classified as “bad data.” These data can cause insecurity to engineering and should be discarded.

Log-normal distribution is used as the distribution of model factor, and the model factor statistics are presented in terms of the mean and coefficient of variation (COV). Based on equations (5) and (6), the updating model factors statistics are obtained in Table 5 for reliability analysis and

resistance factor calculation. The coefficient of variation of updating data is minimum. The coefficient of variation for “general data” is maximum. In summary, the updating model factors are reliable enough to calculate the reliability index and resistance factor of bored piles.

According to reliability theory, the limit state equation of bored pile capacity is [16]:

$$g(R, Q_D, Q_L) = R - Q_D - Q_L, \quad (9)$$

where R is vertical pile capacity (kN); Q_D is dead load (kN); and Q_L is live load (kN). Three methods are employed to calculate the reliability index.

3.1. First-Order Reliability Method. If the three parameters in equation (9) obey log-normal distribution, the calculation formula of reliability index can be written as [6]

$$\beta = \frac{\ln \left(\left((\lambda_R \text{FOS} ((Q_D/Q_L) + 1)) / (\lambda_{QD} (Q_D/Q_L) + \lambda_{QL}) \right) \sqrt{((1 + \text{COV}_{QD}^2 + \text{COV}_{QL}^2) / (1 + \text{COV}_R^2))} \right)}{\sqrt{\ln(1 + \text{COV}_R^2)(1 + \text{COV}_{QD}^2 + \text{COV}_{QL}^2)}}, \quad (10)$$

TABLE 2: Load testing data of pile capacity in cohesive soil.

Case number	D_s (mm)	D_B (mm)	L (m)	s (mm)	Q_p (kN)	Q_m (kN)	a	b
34	600	600	9	0.59	4807	4800	0.48	0.96
35	600	600	11.5	2.7	6447	4100	2.87	0.82
36	750	750	21.8	2.34	6521	7100	3.55	0.71
37	350	350	17.3	0.18	1398	760	0.05	0.99
38	610	610	6.5	21.19	2062	2300	3.40	0.80
39	600	600	6.5	13.5	3280	3100	4.96	0.84
40	600	800	24	12	2545	3360	12.43	0.64
41	610	610	9	22.9	3040	2650	5.30	0.72
42	610	610	7	1.65	2235	1800	1.08	0.90
43	750	750	13	37	4179	3700	3.05	0.80
44	450	450	9	1.79	3658	2930	1.76	0.88
45	350	350	5	1.7	1196	1700	2.55	0.76
46	500	500	6	1.7	2333	1900	2.85	0.76
47	600	600	6	85.3	707	520	2.65	0.62
48	450	450	6	20.3	1225	1175	0.82	0.94
49	300	300	6	14.1	975	1080	1.19	0.86
50	600	600	9.6	4.4	3223	3500	2.92	0.80
51	400	400	8.7	2.9	1221	1240	0.82	0.93
52	350	350	8.7	9	834	825	1.76	0.84
53	410	410	11	0.95	1444	1450	1.45	0.87
54	615	615	12	36	2375	3000	4.83	0.75
55	615	615	12	35	1948	2450	3.92	0.74
56	610	610	7	25.4	1184	1400	2.43	0.72
57	610	610	1.5	17.8	462	510	1.00	0.93
58	500	500	7.8	5.58	2392	3600	2.67	0.84
59	430	430	6.5	4.49	907	1150	3.36	0.74
60	450	600	15.5	4.19	1818	2310	2.98	0.82
61	750	750	10.2	1.89	5869	8500	3.94	0.79
62	450	450	8	45.53	1292	1230	8.40	0.50
63	450	450	8	22.7	1292	1820	1.66	0.85
64	450	450	8	3.93	2110	2580	1.52	0.89
65	450	450	8	4.83	2110	2670	2.14	0.86
66	450	450	8	4.0	2110	2790	2.39	0.84
67	450	450	8	3.35	2110	2900	2.20	0.85
68	450	450	8	2.85	2110	4200	3.86	0.76
69	450	450	8	3.2	1602	2800	1.74	0.87
70	450	750	4.5	2.96	8906	9600	4.22	0.76
71	430	430	7	1.19	1156	1660	1.67	0.86
72	550	550	6	6.57	2916	4800	1.46	0.90
73	910	910	12	1.3	5088	7050	1.07	0.92
74	910	910	9	1.8	5088	5900	0.99	0.93
75	910	910	9	1.16	7648	9700	4.58	0.72
76	910	910	9	0.68	4721	7000	1.78	0.86
77	530	430	8	3.38	1955	1880	3.63	0.75
78	600	600	14.9	2.13	4230	5430	3.48	0.79
79	600	600	14.6	3.26	4196	3000	1.31	0.92
80	750	750	15.4	2.35	6153	6250	1.93	0.89
81	600	600	14.7	1.74	4207	4450	1.95	0.87
82	750	750	15.7	1.95	10172	13000	5.37	0.75
83	500	500	7.2	2.2	3294	3300	1.64	0.87
84	750	750	7.2	1.6	6266	4810	0.88	0.93
85	500	500	7.2	9.5	1901	2200	2.79	0.81
86	750	750	7.2	7.2	3515	5300	4.03	0.77

Note. D_s is the pile shaft diameter; D_B is the pile bottom diameter; L is the pile length; s is the final settlement of load tests; a and b are two hyperbolic curve-fitting parameters.

where FOS is the factor of safety according to allowable stress design method; λ_{QD} and λ_{QL} are the partial factors of dead load and live load, respectively; COV_{QD} and COV_{QL} are the coefficients of variation of dead load and live load, respectively;

Table 5 gives the means and coefficients of variation for “updating data,” “good data,” and “general data,” and the specifications give the load statistics; then the reliability index can be calculated using equation (10), which is described as β_{MVF} .

FIGURE 1: Normalized load-settlement curves of load test data.

FIGURE 2: The scatter diagram of testing pile capacity and calculation pile capacity.

TABLE 3: Classified results of load test data in noncohesive soil.

Good data			General data		
Case number	λ_R	ζ_i	Case number	λ_R	ζ_i
1	1.04	0.02	14	0.80	0.22
2	1.22	0.20	18	1.02	0.00
3	1.11	0.09	19	0.79	0.22
4	0.97	0.05	20	0.97	0.05
5	1.13	0.11	21	1.27	0.24
6	1.15	0.13	23	0.99	0.03
7	0.93	0.09	29	0.78	0.23
8	1.02	0.00	30	0.86	0.16
10	0.83	0.18	31	0.90	0.11
11	0.97	0.04	32	1.00	0.00
13	1.03	0.01	—	—	—
			9	0.71	0.30
			12	1.31	0.29
			16	0.74	0.27
			17	1.32	0.30
			22	1.33	0.30
			27	0.66	0.35
			28	0.65	0.36
			33	1.50	0.47
			—	—	—
			—	—	—
			—	—	—

3.2. Design Point Method. The limit-state function is linear at a point on the failure surface; its performance function is [6]

$$g = \ln \left(\frac{\text{FOS} \lambda_R ((Q_D/Q_L) + 1)}{\lambda_{QD} (Q_D/Q_L) + \lambda_{QL}} \right). \quad (11)$$

All the parameters in equation (11) have the same meanings as equation (10). The calculation can be carried out using MATLAB software, which is described as β_{AF} .

3.3. Monte Carlo Simulation Method. Monte Carlo simulation method is an accuracy method to calculate reliability index, which is employed for comparison with the

FIGURE 3: Reliability index in noncohesive soil. (a) First-order reliability method. (b) Design point method. (c) Monte Carlo simulation method.

If the reliability index is calculated using equation 11), the limit state equation for resistance factor calculation is

$$g_{\varphi} = \ln \left(\frac{\lambda_R (\gamma_{QD} (Q_D/Q_L) + \gamma_{QL})}{\phi (\lambda_{QD} (Q_D/Q_L) + \lambda_{QL})} \right) = 0. \quad (15)$$

The resistance factor is described as ϕ_{AF} according to equation (15).

If the reliability index is calculated using equation (12), the limit state equation for resistance factor calculation is

$$g = \left(\frac{\lambda_R}{\phi} \right) \left(\gamma_{QD} \frac{Q_D}{Q_L} + \gamma_{QL} \right) - \left(\lambda_{QD} \frac{Q_D}{Q_L} + \lambda_{QL} \right) = 0. \quad (16)$$

The resistance factor is described as ϕ_{MCS} according to equation (16).

2.0, 2.5, and 3.0 are selected as the target reliability index. Based on equations (14)–(16), the calculation results of resistance factor are shown in Table 6.

The quality of data has distinct contribution to resistance factor of bored piles. The accuracies of design point method and Monte Carlo simulation method are satisfactory, which can be considered as the criterion to verify the accuracy of proposed method. The results based on two methods are larger than the results based on first-order reliability method, and the difference are 6.9% and 18.3%, respectively. Meanwhile, the difference between the two methods is near 0. The accuracies based on “good data” and “updating data” are better than the accuracies based on “general data” and “all data.”

In summary, Table 7 shows the recommended values of resistance factors. However, the reliability theory of pile

FIGURE 4: Reliability index in cohesive soil. (a) First-order reliability method. (b) Design point method. (c) Monte Carlo simulation method.

TABLE 6: Calculation results of resistance factor.

Target reliability, β_T	Noncohesive soil			Cohesive soil		
	ϕ_{MvF}	ϕ_{AF}	ϕ_{MCS}	ϕ_{MvF}	ϕ_{AF}	ϕ_{MCS}
All data						
2.0	0.440	0.452	0.450	0.461	0.476	0.475
2.5	0.375	0.389	0.389	0.387	0.396	0.394
3.0	0.336	0.354	0.353	0.344	0.362	0.360
General data						
2.0	0.437	0.446	0.445	0.443	0.450	0.450
2.5	0.371	0.382	0.380	0.375	0.385	0.384
3.0	0.333	0.350	0.350	0.335	0.347	0.345
Good data						
2.0	0.440	0.446	0.445	0.467	0.475	0.474
2.5	0.376	0.385	0.385	0.391	0.399	0.399
3.0	0.337	0.348	0.347	0.346	0.356	0.354

TABLE 6: Continued.

Target reliability, β_T	Noncohesive soil			Cohesive soil		
	ϕ_{MvF}	ϕ_{AF}	ϕ_{MCS}	ϕ_{MvF}	ϕ_{AF}	ϕ_{MCS}
Updating data						
2.0	0.440	0.449	0.448	0.463	0.472	0.471
2.5	0.376	0.385	0.384	0.390	0.400	0.400
3.0	0.337	0.348	0.348	0.345	0.358	0.356

TABLE 7: Recommended values of resistance factors.

β_T	Noncohesive soil	Cohesive soil
2.0	0.456	0.473
2.5	0.386	0.400
3.0	0.347	0.356

foundation is not perfect enough to be applied in engineering fact. The recommended values are proposed only according to the calculation results and American LRFD for Bridge Design Specification. Its application in engineering field needs to be further studied.

4. Conclusions

From this study, some conclusions are presented:

- (1) The proposed method incorporating probability theory and Bayesian method can not only classify the in situ data but also overcome the deficiency caused by small sample for accuracy data.
- (2) Data classification has significant contribution to reliability index and resistance factor. The results according to “good data” and “updating data” are larger than the results according to “general data” and “all data.” Meanwhile the difference of results using two types of data is near 0. Therefore, “good data” and “updating data” can be used as the basis of resistance factor calculation.
- (3) Reliability index and resistance factor are sensitive to the type of soil, and the calculation results in cohesive soil are larger than the results in noncohesive soil.
- (4) The recommended values are proposed only according to the calculation results and American LRFD for Bridge Design Specification. Its application in engineering fact needs to be further studied. However, the proposed method can be used to update other geotechnical data.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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