

Article

Incorporating Setup Effects into the Reliability Analysis of Driven Piles

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Abstract: Driven-pile setup is referred to a phenomenon in which the bearing capacity of driven piles increases with time after the end of driving (EOD). The setup effect can significantly improve the bearing capacity (ultimate resistance) of driven piles after initial installation, especially the ultimate shaft resistance. Based on the reliability theory and considering the setup effects of driven piles, this article presents an increase factor (M_{setup}) for the ultimate resistance of driven piles to modify the reliability index calculation formula. At the same time, the correlation between R_0 and R_{setup} is comprehensively considered in the reliability index calculation. Next, the uncertainty analysis of load and resistance is conducted to determine the ranges of relevant parameters. Meanwhile, the influence of four critical parameters (factor of safety FOS, the ratio of dead load to live load $\rho = Q_D/Q_L$, M_{setup} , the correlation coefficient between R_0 and R_{setup} , and $\rho_{R_0, R_{\text{setup}}}$) on reliability index are analyzed. This parametric study indicates that ρ has a slight influence on the reliability index. However, the reliability index is significantly influenced by FOS, M_{setup} , and $\rho_{R_0, R_{\text{setup}}}$. Finally, by comparisons with the existing results, it is concluded that the formula proposed in this study is reasonable, and more uncertainties are considered to make the calculated reliability index closer to a practical engineering application. The presented formula clearly expresses the incorporation of the pile setup effect into reliability index calculation, and it is conducive to improving the prediction accuracy of the design capacity of driven piles. Therefore, the reliability analysis of driven piles considering setup effects will present a theoretical basis for the application of driven piles in engineering practice.

Keywords: driven piles; bearing capacity; setup; reliability; correlation coefficient



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1. Introduction

Piles that are driven into the soil usually show an increase in bearing capacity (ultimate resistance) over time after EOD, which is often referred to as the setup effect of driven piles. This phenomenon is reported by many geotechnical engineers. Tavenas and Audy [1] first put forward the setup effect of driven piles. Samson and Authier [2] illustrated four cases in which the bearing capacity of piles changed significantly over time. Basu et al. [3] investigated the jacking of piles in clay by finite element method. Komurka et al. [4] proposed a large number of references related to the topic of pile setup. Ng et al. [5] developed a method for quantifying pile setup by using recent field tests when the steel H-piles were driven into clay. The soil setup phenomenon is mainly composed of three factors: (1) excess pore water pressure dissipation, (2) thixotropic effect, and (3) aging effect [6]. Driven piles have obvious disturbance and remodeling effects on the soil around the pile, which makes the pore water pressure dissipate. Therefore, the effects of setup on pile resistance depend on the type of soil in which the pile is driven.

As for the bearing capacity of piles, along with some of the most traditional and commonly used methods among practitioners [7–11], there are more recent approaches, which are based on, for example, the finite element method [12–14]. Meanwhile, some researchers [15–17] indicated that pile setup phenomena should be formally included in the forecast technique of total pile resistance as experience and understanding of the

phenomenon grew. For the purpose of predicting the pile's side resistance at a specific time after EOD and incorporating its influence into the pile design, Bullock et al. [18] presented a conservative method in which the side shear setup was included in pile resistance design. Due to different uncertainties associated with EOD resistance and setup resistance, Komurka et al. [19] proposed an approach to split factors of safety into EOD and setup parts in terms of pile capacity, and this method was especially suitable for load and resistance factor design (LRFD).

LRFD is the most important and potential class of reliability-based design approaches, which commonly can quantitatively incorporate more uncertainties into the design process, in particular for uncertainties in loads and resistances [20]. Some research studies [21] were conducted to incorporate the setup effects on the LRFD resistance factor into deep foundation design. Yang and Liang [22] added setup resistance into the LRFD of driven piles. Bian et al. [23] suggested a method for a reliability-based design that takes setup effects into account. Despite the fact that full-scale load tests were undertaken for driven piles with setup effects, and a substantial amount of data was acquired [24], the setup resistance of driven piles was rarely used to the maximum extent due to large uncertainties in the driving process. Therefore, the focus of this study is to establish a model for reliability analysis of driven piles considering setup effects.

First, this paper presents a novel reliability index formula for driven piles by incorporating setup into the reliability evaluation method. Second, the range of relevant parameters is determined by the uncertainty analysis of load and resistance. Next, the influence of four critical parameters (factor of safety FOS; the ratio of dead load to live load $\rho = Q_D/Q_L$; the ratio of setup resistance to initial ultimate resistance M_{setup} ; the correlation coefficient between R_0 and R_{setup} , $\rho_{R_0, R_{\text{setup}}}$) on the reliability index are analyzed. Finally, through a validation example analysis, it is verified that the method proposed in this study is reasonable, and it is concluded that the method proposed in this study is more accurate in calculating the reliability index and considers more uncertainties.

2. Basic Assessment Methods for Pile Setup

Pile setup is the increase in axial bearing capacity of the pile driving into the soil with time. As a result, the ultimate resistance is divided into two components, R_0 and R_{setup} , as shown in the following equation:

$$R = R_0 + R_{\text{setup}} \quad (1)$$

where R is the ultimate resistance; R_0 is the initial ultimate resistance; R_{setup} is the setup resistance.

Equation (1) emphasizes the importance of appropriately assessing setup resistance for reliability evaluation methods. Therefore, this was a topic that drew the attention of many practitioners and presented empirical relationships for predicting the pile setup. These empirical equations are listed in Table 1. Among existing equations, the logarithmic empirical relationship by Skov and Denver [25] has been widely utilized to predict the pile setup, which is,

$$R_{\text{setup}} = R_0 A \log \frac{t}{t_0} \quad (2)$$

where A is a variable that varies depending on the soil type; t is the time since the initial pile driving ended; t_0 is the initial time.

Table 1. Empirical equation for predicting setup resistance of driven piles.

Reference	Equation	Comments
Skov and Denver [25]	$R_t = R_0 \left(1 + A \log \frac{t}{t_0}\right)$	$t_0 = 1.0$ and $A = 0.6$ in clay; $t_0 = 0.5$ and $A = 0.2$ in sand; R_t is the predicted resistance at time t after driving; R_0 is the measured resistance at time t_0 .
Long et al. [3]	$R_t = 1.1 R_{EOD} t^\alpha$	Values of α : average = 0.13, lower bound = 0.05, and upper bound = 0.18. R_{EOD} is the measured resistance at the EOD.
Svinkin et al. [26]	$R_t = B R_{EOD} t^{0.1}$	Values of B : lower bound = 1.025, and upper bound = 1.4.
Bogard and Matlock [27]	$R_t = R_u \left[0.2 + 0.8 \left(\frac{t/T_{50}}{1+t/T_{50}}\right)\right]$	R_u is the ultimate resistance with 100% of setup realized, T_{50} is the time required to realize 50% of pile setup.

3. Estimation of the Reliability Index of Driven Piles

3.1. General Reliability Evaluation Method of Driven Piles

In engineering practice, there are many factors that affect the bearing capacity of driven piles, including pile geometry size, soil type, spatial randomness, variability, etc. At present, the measurement error of soil physical properties and the influence of the pile forming process on soil properties cannot be accurately analyzed, and the main factors affecting pile bearing capacity can only be reflected in the uncertainty of parameters for calculating bearing capacity [28]. The following limit state equation is established to analyze the reliability of driven piles:

$$g = R - Q = 0 \quad (3)$$

The load effect Q , herein, only includes the combination of dead load Q_D and live load Q_L ; therefore, the reliability index β can be estimated using the following reliability method [29]:

$$\beta = \frac{\ln \left[\frac{\lambda_R R_n}{\lambda_{QD} Q_D + \lambda_{QL} Q_L} \sqrt{\frac{1 + \text{COV}_{QD}^2 + \text{COV}_{QL}^2}{1 + \text{COV}_R^2}} \right]}{\sqrt{\ln \left[\left(1 + \text{COV}_R^2\right) \left(1 + \text{COV}_{QD}^2 + \text{COV}_{QL}^2\right) \right]}} \quad (4)$$

where λ_R , λ_{QD} , and λ_{QL} are the bias factors for resistance, dead load, and live load, respectively; COV_R , COV_{QD} , and COV_{QL} are the coefficients of variation (COVs) for resistance, dead load, and live load, respectively.

3.2. Setup Effect in Reliability Evaluation of Driven Piles

When the setup effect is incorporated into the driven pile design, the limit state function can be expressed as

$$g = R_0 + R_{\text{setup}} - Q_D - Q_L = 0 \quad (5)$$

In this work, the increase factor for the ultimate resistance is defined as the proportion of setup resistance to initial ultimate resistance, represented as M_{setup} by Equation (6).

$$M_{\text{setup}} = \frac{R_{\text{setup}}}{R_0} \quad (6)$$

Then, Equation (7) is derived using Equation (6) and LRFD method [29].

$$\frac{\lambda_R R_n}{\lambda_{QD} Q_D + \lambda_{QL} Q_L} = \frac{(\lambda_{R0} + \lambda_{R\text{setup}} M_{\text{setup}}) \text{FOS}(Q_D + Q_L)}{\lambda_{QD} Q_D + \lambda_{QL} Q_L} = (\lambda_{R0} + \lambda_{R\text{setup}} M_{\text{setup}}) \frac{\text{FOS}(\rho + 1)}{\lambda_{QD} \rho + \lambda_{QL}} \quad (7)$$

where $\rho = Q_D/Q_L$; FOS is the factor of safety.

The computation formula for the reliability index of driven piles considering setup effects can be obtained by substituting Equation (7) into Equation (4) as follows:

$$\beta = \frac{\ln \left[(\lambda_{R0} + \lambda_{Rsetup} M_{setup}) \frac{FOS(\rho+1)}{\lambda_{QD}\rho + \lambda_{QL}} \sqrt{\frac{1+COV_{QD}^2+COV_{QL}^2}{1+COV_{R0}^2+COV_{Rsetup}^2}} \right]}{\sqrt{\ln \left[(1 + COV_{R0}^2 + COV_{Rsetup}^2) (1 + COV_{QD}^2 + COV_{QL}^2) \right]}} \tag{8}$$

As there is an inescapable interplay between R_0 and R_{setup} , the connection between R_0 and R_{setup} should be taken into account in reliability analysis. When considering the correlation between R_0 and R_{setup} , the reliability index of driven piles is expressed as follows:

$$\beta = \frac{\ln \left[(\lambda_{R0} + \lambda_{Rsetup} M_{setup}) \frac{FOS(\rho+1)}{\lambda_{QD}\rho + \lambda_{QL}} \sqrt{\frac{1+COV_{QD}^2+COV_{QL}^2}{1+COV_{R0}^2+2\rho_{R0,Rsetup}COV_{R0}COV_{Rsetup}+COV_{Rsetup}^2}} \right]}{\sqrt{\ln \left[(1 + COV_{R0}^2 + 2\rho_{R0,Rsetup}COV_{R0}COV_{Rsetup} + COV_{Rsetup}^2) (1 + COV_{QD}^2 + COV_{QL}^2) \right]}} \tag{9}$$

where $\rho_{R0,Rsetup}$ is the correlation coefficient between R_0 and R_{setup} .

The relationship between failure probability and reliability index can be calculated with the following function:

$$P_f = 1 - NORMDIST(\beta) \tag{10}$$

3.3. Uncertainties of Loads and Resistances

The mean (or bias factor), coefficient of variation, distribution type, and other factors are used to describe the uncertainty of random variables. The terms normal and lognormal are frequently used to characterize the load and resistance distributions of engineering constructions [30]. The probabilistic features of loads and resistances for driven piles described in Table 2 were employed for this investigation [21,22,29,31].

Table 2. Probabilistic characteristics of random variables of loads and resistances.

Random Variable	Bias Factor, λ	Standard Deviation, σ	Coefficient of Variation, COV	Distribution	Reference
R_0	1.158	0.393	0.339	Log-normal	Paikowsky et al. [21]
R_{setup}	1.141	0.543	0.475	Normal	Yang and Liang [22]
	1.023	0.593	0.580	Log-normal	Yang and Liang [31]
Q_D	1.080	0.140	0.130	Log-normal	AASHTO [29]
Q_L	1.150	0.207	0.180	Log-normal	AASHTO [29]

Many researchers reported the $\rho = Q_D/Q_L$ for bridge constructions and speculated that it varies with bridge span lengths [32,33]. Meanwhile, Hansell et al. [32] adopted a formula to express the relationship between the ratio of $\rho = Q_D/Q_L$ and the length of the bridge span, which is,

$$\frac{Q_D}{Q_L} = (1+I)(0.0132l) \tag{11}$$

where I is the dynamic load factor, and l is the bridge span length in feet. When the bridge span length l varies from 10 m to 70 m, the value of $\rho = Q_D/Q_L$ virtually spread out from 0.576 to 4.0, according to Equation (11). As a result, for this investigation, values ranging from 0.5 to 4.0 for $\rho = Q_D/Q_L$ were chosen.

The increase factor (M_{setup}) is re-expressed by using Equations (2) and (6).

$$M_{setup} = A \log \frac{t}{t_0} \tag{12}$$

M_{setup} estimation is dependent on parameters A and $\log(t/t_0)$, as shown in Equation (12). Yang and Liang [22,31] summarized databases that contained both static and dynamic load test results of driven piles in clay and sand, with the value of A ranging from 0.1 to 1.0. Furthermore, time t following EOD varied between 1 and 100 days in the majority of cases, with $\log(t/t_0)$ with $t_0 = 1$ ranging between 0 and 2. As a result of the analysis of A and $\log(t/t_0)$, the increase factor (M_{setup}) for this study was determined to be between 0 and 2.

4. Reliability Analysis

4.1. The Effect of FOS on Reliability Index

Firstly, the effect of FOS on the reliability indices of driven piles considering setup effects is studied. The bias factors (λ) and coefficients of variation (COV) of loads and resistances of driven piles are summarized in Table 2, and the value of 1.0 for the increase factor M_{setup} were also used. Meanwhile, based on the analysis results on the effect of ρ on reliability index, the value of $\rho = 3.69$ (65 m span length) was accepted for study [34,35]. Reliability analysis was performed for the FOSs ranging from 1.0 to 5.0. The correlation between R_0 and R_{setup} was not taken into account in this part. Finally, Figure 1 shows the reliability indices corresponding to the factor of safety of driven piles in clay and sand.

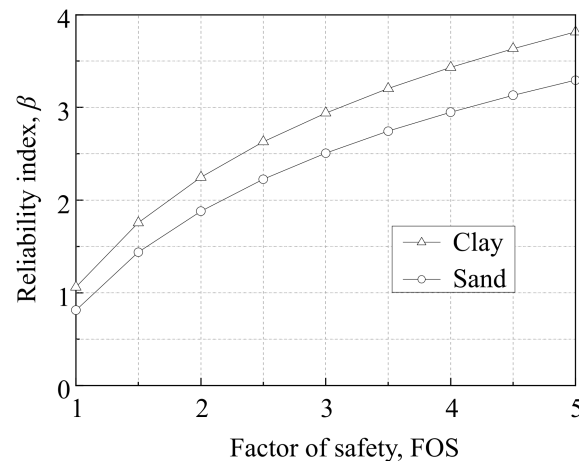


Figure 1. Reliability indices with FOS for driven piles in clay and sand.

The variations in the reliability index with FOS, shown in Figure 1, obviously illustrate that the reliability indices of driven piles increase as FOS increases. This indicates the significant influence of FOS on reliability evaluation results of driven piles. In addition, the rate of increase in the reliability index corresponding to FOS slowly decreases with increasing FOS; a value of 3.0 for FOS is a key point in the transition zone of increase rate in Figure 1. Therefore, the value FOS = 3.0 can be used in later studies.

4.2. The Effect of ρ on Reliability Index

The purpose of this subsection is to investigate the impact of ρ on the reliability index of driven piles considering setup effects. The λ and COV of loads and resistances for driven piles in Table 2 are used, FOS was designed as 3.0, and the value 1.0 for the increase factor (M_{setup}) was adopted. In this part, the correlation between R_0 and R_{setup} was not considered. Based on these proposed values of critical parameters, the reliability index of driven piles can be calculated using Equation (8). Figure 2 describes the variations in the computed reliability index with $\rho = Q_D/Q_L$ of driven piles.

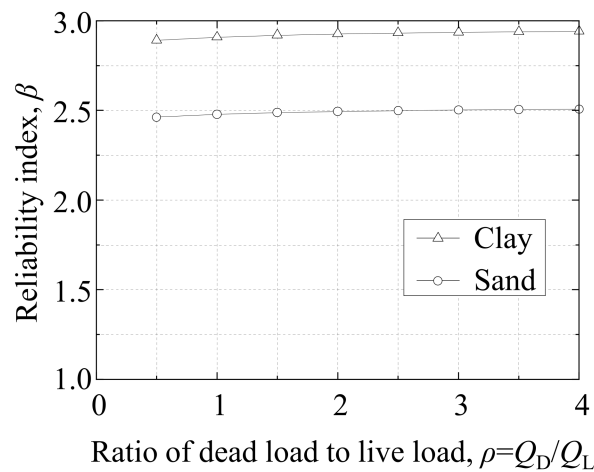


Figure 2. Reliability indices with $\rho = Q_D/Q_L$ for driven piles in clay and sand.

It can be seen from Figure 2 that the reliability indices are insensitive to the variations in $\rho = Q_D/Q_L$ for driven piles, which is consistent with other research in this field [36,37]. Notably, this conclusion is beneficial to the selection of ratio $\rho = Q_D/Q_L$ in further studies, and it is also reasonable to take $\rho = Q_D/Q_L$ as a constant for the other similar research.

4.3. The Effect of M_{setup} on Reliability Index

In this subsection, the effect of M_{setup} on the reliability index of driven piles considering setup effects is studied. The λ and COV of loads and resistances for driven piles in Table 2 were used, and the value FOS = 3.0 and $\rho = 3.69$ were obtained from the analysis of the first two subsections. Reliability analysis was performed for the increase factor M_{setup} ranging from 0 to 2.0. In this part, the correlation between R_0 and R_{setup} was not taken into account. Figure 3 shows the reliability indices corresponding to M_{setup} of driven piles.

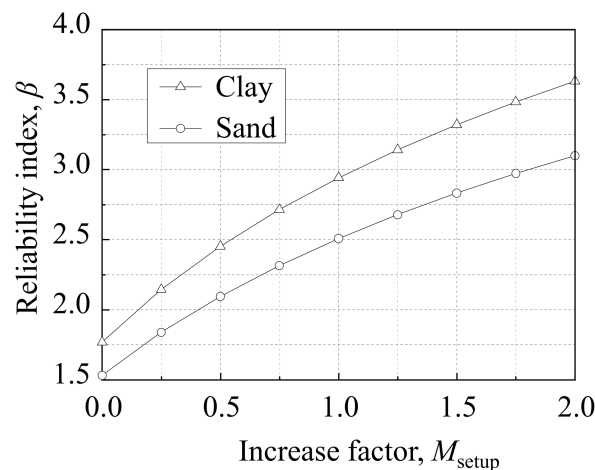
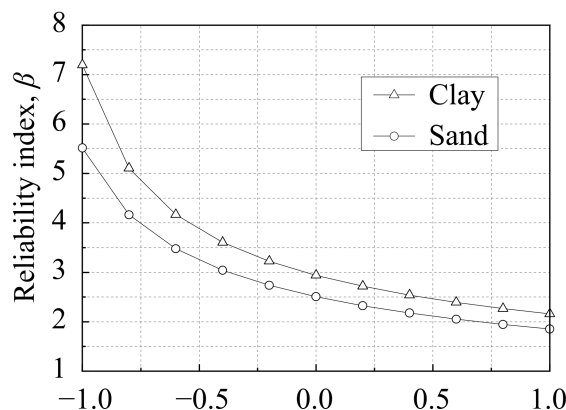


Figure 3. Reliability indices with M_{setup} for driven piles in clay and sand.

The results show that in clay and sand, the reliability indices of driven piles increase with rising M_{setup} , and the growth rates decrease slowly. Additionally, it also can be seen that reliability indices of the driven pile in clay are larger than those in the sand; the difference between them is about 15.5% for a given M_{setup} . This is because the soil around the pile will be disturbed in the process of pile driving, which will lead to the dissipation of pore water pressure and the consolidation of soil. Then, the degree of consolidation of soil is affected by the cohesion of soil, so the corresponding reliability index of different soil will be different.

4.4. The Effect of $\rho_{R_0, R_{setup}}$ on the Reliability Index

In this subsection, the effect of $\rho_{R_0, R_{setup}}$ on the reliability index of driven piles considering setup effects is studied. The λ and COV of loads and resistances for driven piles in Table 2, FOS = 3.0, $M_{setup} = 1.0$, and $\rho = 3.69$ were used. The reliability index of driven piles was computed using Equation (9) for $\rho_{R_0, R_{setup}}$, ranging from -1.0 to 1.0 . Figure 4 depicts the reliability indices corresponding to $\rho_{R_0, R_{setup}}$ of driven piles.



Correlation coefficient between R_0 and R_{setup} , $\rho_{R_0, R_{setup}}$

Figure 4. Reliability indices with $\rho_{R_0, R_{setup}}$ for driven piles in clay and sand.

The results show that in clay and sand, the reliability indices of driven piles decrease with rising $\rho_{R_0, R_{setup}}$; however, the decrease rate of reliability indices with $\rho_{R_0, R_{setup}}$ between -1.0 and 0 is significantly greater than those with $\rho_{R_0, R_{setup}}$ between 0 and 1.0 for clay and sand.

5. Validation Example

In order to verify the accuracy of the formula proposed in this paper, it was compared with the formula proposed by Haque et al. [17]. At the same time, the data in the Case Pile Wave Analysis Program (CAPWAP) were compared; the measured and predicted resistance values of 19 test piles are relisted in Table 3 [17]. For calculating the reliability index, the corresponding load statistical parameters, such as $\lambda_R = 1.335$, $COV_R = 0.325$ [21], $\lambda_{QD} = 1.080$, $\lambda_{QL} = 1.150$, $COV_{QD} = 0.130$, $COV_{QL} = 0.180$ [29], were considered. Meanwhile, the statistical parameters of setup resistance were calculated at four different intervals of 14 days after EOD (i.e., 30, 45, 60, and 90 days after drive). The values of λ_{setup} are 1.218, 1.092, 1.059, and 1.033, respectively, and the values of COV_{setup} are 0.641, 0.62, 0.64, and 0.66, respectively.

As for the value of the four critical parameters proposed in this study, the conclusion drawn from the “Reliability Analysis” in Section 4 shows that the value of FOS is 3.0, and the value of ρ is 3.69. Referring to the parameter A model proposed by Haque et al. [17], the value of A in clay and sand are 0.31 and 0.15, respectively. In this study, the values of M_{setup} was calculated using Equation (12) at four different intervals of 14 days after EOD (i.e., 30, 45, 60 and 90 days after driving), which are 0.551, 0.606, 0.645, 0.699 in clay, and 0.267, 0.293, 0.312, 0.338 in sand, respectively. According to the values of R_0 and R_{setup} shown in Table 3, the value of $\rho_{R_0, R_{setup}}$ can be calculated as 0.312, 0.387, 0.386, and 0.378 at four different time intervals.

The findings of computing the reliability index using the formulas presented by Haque et al. [17] and presented by this study are summarized in Table 4, and the curve of reliability index is drawn together with time interval, as shown in Figure 5. When the correlation between R_0 and R_{setup} is considered, the reliability index calculated by the formula proposed in this paper is not significantly different from that calculated by the formula proposed in Haque et al. [17], which is usually around 0.3. As a result, this conclusion shows that the formula proposed in this study is feasible. When the correlation

between R_0 and R_{setup} is not considered, the difference between the results calculated in this study and those calculated by the formula proposed by Haque et al. [17] is about 0.5. Although the results are slightly higher, the correlation between R_0 and R_{setup} is considered, and more uncertainties in the piling process are investigated, bringing the results closer to engineering application.

Table 3. Resistance information of 19 test piles by the Case Pile Wave Analysis Program.

Nos.	Project Name	Resistance of 14 Day (kN)	Resistance Increased with Respect to 14 Days (kN)							
			R_{30-14}		R_{45-14}		R_{60-14}		R_{90-14}	
			Mea	Pre	Mea	Pre	Mea	Pre	Mea	Pre
1	Bayou liberty	356	147	147	227	222	280	276	360	356
2	US 90 LA	222	156	98	196	147	222	182	262	236
3	Calcasieu River TP-2	4310	289	365	445	556	556	694	707	885
4	St. Louis Canal Bridge	178	93	62	120	98	138	120	165	151
5	Morman Slough TP-1	1401	125	151	182	231	227	289	289	369
6	Bayou Bouef (west)	592	182	102	231	156	262	196	311	249
7	Fort Buhlow	409	71	67	111	102	138	129	173	165
8	Caminada Bay TP-3	556	485	356	743	547	925	681	1188	867
9	Caminada Bay TP-5	712	574	302	498	463	618	574	792	734
10	Caminada Bay TP-6	565	338	343	516	529	645	658	823	841
11	Caminada Bay TP-7	222	173	191	267	298	329	369	423	472
12	Bayou Lacasine TP-1	1601	311	111	360	173	396	218	445	276
13	LA-1 TP-2	387	178	173	271	262	334	329	427	418
14	LA-1 TP-4a	770	360	356	556	547	694	681	885	872
15	LA-1 TP-4b	3189	494	614	756	939	943	1170	1205	1495
16	LA-1 TP-5a	787	294	294	449	449	560	560	716	721
17	LA-1 TP-5b	1721	187	254	285	387	356	485	454	618
18	LA-1 TP-6	894	351	347	538	534	672	667	859	854
19	LA-1 TP-10	574	116	111	178	173	222	214	280	276

Note: Mea = measured resistance. Pre = predicted resistance. R_{30-14} , R_{45-14} , R_{60-14} , R_{90-14} = setup resistances at 30, 45, 60, and 90 days after 14 days, respectively. Nos = Numbers.

Table 4. Summary of reliability index.

Type of Soil	Time Intervals (30, 45, 60, and 90 Days after End of Driving) after the 14 Days from EOD											
	Results of Haque et al. (2018)				Results of This Paper (not Considering Correlation Coefficient between R_0 and R_{setup})				Results of This Paper (Considering Correlation Coefficient between R_0 and R_{setup})			
	30–14	45–14	60–14	90–14	30–14	45–14	60–14	90–14	30–14	45–14	60–14	90–14
Clay	1.976	1.942	1.917	1.899	1.646	1.657	1.652	1.654	1.462	1.466	1.460	1.464
Sand	1.976	1.942	1.917	1.899	1.482	1.495	1.486	1.481	1.299	1.304	1.294	1.291

Compared with Haque et al. [17], this paper proposes a critical parameter (M_{setup}), which is suitable for various soil types and takes more uncertainties into account, providing a more comprehensive theoretical basis for future research. Figure 5 further demonstrates that the reliability index for the driven pile considering setup effects in clay is much higher than that of the driven pile in sand, which is consistent with the conclusion of Section 4 “Reliability Analysis”.

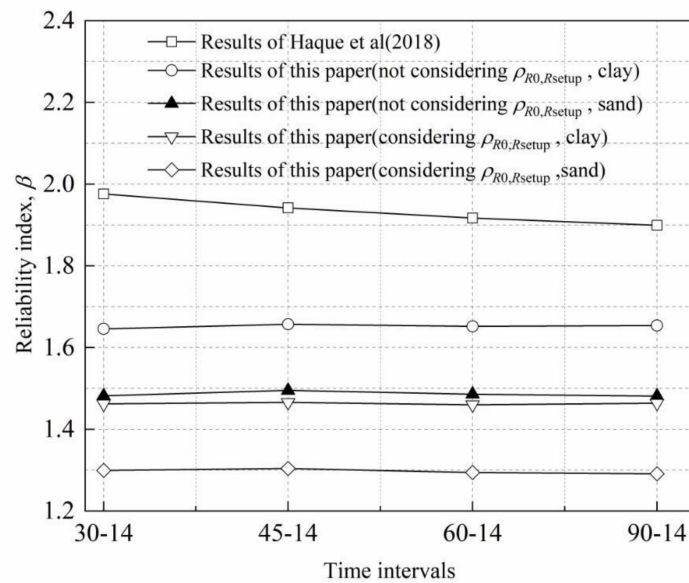


Figure 5. Reliability indices with time intervals for driven piles in clay and sand.

6. Conclusions

This paper presented an increase factor for the ultimate resistance for driven piles to modify the reliability index calculation formula. Meanwhile, the study conducted the uncertainty analysis of load and resistance to determine the ranges of relevant parameters. Finally, the impact of four critical parameters on the reliability index were investigated and compared with the existing results.

Through parameter analysis, it is concluded that FOS has a significant influence on the reliability index of driven piles considering setup effects. The reliability index is essentially unaffected by $\rho = Q_D/Q_L$, so it can be used as a constant when calculating the reliability index. M_{setup} was a critical parameter in this study and has a significant impact on the reliability index of driven pile considering setup effects. Therefore, the value of M_{setup} is particularly important in the reliability analysis of driven piles considering setup effects and is generally selected according to the type of soil. Meanwhile $\rho_{R0,Rsetup}$ has a significant influence on the reliability index of driven piles, and when the $\rho_{R0,Rsetup}$ value is smaller, the corresponding reliability index is higher. Through validation example analysis, the proposed formula in this paper is feasible. Additionally, it is concluded that more uncertainties will be considered when using the formula proposed in this paper to calculate the reliability index of driven pile considering setup effects.

To summarize, if the setup effect is not entirely considered, the reliability index obtained is very conservative. Therefore, the reasonable evaluation of setup effects is crucial for the reliability analysis of driven piles.

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