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Calibration of Safety Factor for Micropile in Transmission tower Foundations Based on Relative Reliability Approach

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ABSTRACT: This paper determines the design safety factor of micropiles utilized in the foundation of electric power transmission towers against the geotechnical failure due to the compressive force (failure of micropile-soil cohesion) by using the relative reliability approach. On the basis of this approach, the design processes are conducted in a way so that the reliability of foundation would be greater than that of tower. In other words, the failure of tower structure should occur prior to that of foundation. In order to calculate the safety factors in terms of specific reliability level of foundation with respect to tower, reliability analyses were adopted using "Monte Carlo Sampling" method. Furthermore, the strength statistical characteristics of transmission towers and micropiles have been extracted based on the reports of previous tests. The results of which revealed that, considering the target value of Relative Reliability Factor (RRF)- the ratio between failure probabilities of tower to foundation- as 12, the values of safety factors attained in the current research are equal to 2.0 and 2.20 respectively for lattice and pole transmission towers. It should be remarked that these safety factors are only valid in cases of micropile design in dense sandy (SP-SM, SP&GW-GM) and clay-silt (SC, SM&SC-SM) soils.

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1- Introduction

Foundations of power transmission towers are one of the major components in transmission lines. On account of the diversity in properties of soil strata along transmission lines, numerous problems and difficulties associate with their design and construction. In zones with soft soil, the majority of construction cost is allocated to the foundation; whereas in other cases, the foundation construction cost descends to the second place. In some cases, more than 30% of the total construction cost has been designated to the cost related to the foundations of power transmission towers while the tower construction and installation costs were less than 30% of the total cost [1]. Thus, care should be taken in selection and implementation of a foundation, which is expected to enhance the soil bearing capacity and reduce the corrosion effects on reinforcement bars of foundation. From an economic perspective, using micropiles within foundations of transmission lines has become significantly popular in the world due to their various advantages. Micropile is defined as a pile with small diameter (less than 300 mm) which mostly is associated with steel reinforcement and grouting. Not only does a micropile act as a load-bearing and resistant element against the foundation settlement, but it also improves the mechanical characteristics (strength and behavior) of the surrounding soil due to the subsequent grouting operation. On the other hand, concerning the simplicity of execution, no need for excavation and overlapping of the construction stages, using micropile considerably reduces the construction duration in comparison with other foundation types such as pad-chimney, steel grillage and pile foundation. Moreover, independence of any special equipment and consequently saving more time before the executive operations are regarded as the advantages of this technique compared with the conventional foundations such as pad-chimney and pile [2-4].

One of the major challenges in design of power transmission tower foundations is determining or selecting the appropriate safety factor when considering the special conditions of transmission lines. Although the safety requirements are of great importance and must be considered, unnecessary conservatism and increases in cost should be avoided as well. In recent decades, the reliability-based design (RBD) method, which has rationally and economically been established to provide the safety of structures, has also been developed for the foundations and other geotechnical structures. Implementation of the design methods based on the reliability in foundations is linked with many challenges because of relatively high scattering in the mechanical and physical parameters of soils compared with other structural materials [5-8]. Significant efforts have been statistically made to investigate and quantify the variability and statistical characteristics of effective parameters in design of foundations and development of the RBD method for them [9-14]. In this

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field, some research activities have been carried out regarding calibration of partial safety factors for foundations [15, 16]. In connection with power transmission towers, Kulhawy and Phoon performed comprehensive research to determine the statistical characteristics of the soil geotechnical parameters and development of a design methodology for the foundations of transmission lines based on the reliability concept. They studied various types of foundations used in the transmission towers with shallow foundation (pad and chimney) and in-situ piles [17-22].

Many researchers have performed calibration of partial safety factors for different types of deep foundations such as piles, drilled shafts, etc., using reliability analysis methods based on load test data. [23-31]. In light of micropiles, Tonon and Mammino describes the geotechnical and structural, reliability-based design of micropile foundations for a factory in Costa Rica along with its construction issues [32]. Misra et al. developed probability distribution function for micropile pullout capacity and resistance factors obtained for micropile design that can be applied to Load and Resistance factor Design (LRFD) method [33]. To the authors' knowledge, no any specific study has up to now been accomplished on the design of micropile foundations in transmission lines based on the reliability concept, and on determining their design safety factors. There are Handbooks, manual instructions, and relevant standards (e.g. The Federal Highway Administration (FHWA) [34]) that recommend safety factors for micropile design. In this standard, the design safety factors are determined based on the importance and lifetime of bridges as well as the uncertainties in the exerted loads and strength of micropiles. In consequence of the differences in the power transmission towers with other structures, depending on the application, design condition, importance, and lifetime as well as statistical characteristics of climatic loads exerted, the safety factors used for other structures cannot be used for micropiles. Therefore, the safety factors required should be calculated based on the design conditions and requirements of transmission line structures.

In this paper, the design safety factor of a micropile utilized in both lattice and pole towers of a power transmission line foundation against the geotechnical failure due to the compressive force (failure of micropile-soil cohesion) has been determined using the relative reliability approach. On the basis of this approach, the design process is conducted in a way so that the reliability of foundation design would be greater than that of tower. In other words, the failure of tower structure should occur prior to the foundation. In order to determine the safety factor, reliability analysis using "Monte Carlo Sampling" method has been used. The statistical strength characteristics of transmission towers and micropiles were extracted based on the reports of previous tests. Finally, the values of safety factors will be determined and presented for lattice and pole towers.

2- The relative reliability concept in design of transmission lines

Nowadays the reliability-based design (RBD) method has been approved in the most design regulations and standards of structures and their foundations in the world. The main function of this method is establishment of a balance between the structural safety and total costs, from which the unnecessary conservatism leading to increased costs can be avoided while providing the safety required [40]. Using the techniques of reliability theory, the design of structures can be accomplished in a way so that their failure probability at a specific time and load would be in the vicinity of a certain value (target failure probability). Therefore, the extent of conservatism (or reliability level) in the structures designed using this method becomes uniform and balanced.

The majority of transmission line design standards such as ASCE-74 [35] and IEC60826 [36] include a concept namely relative reliability. The relative reliability is defined as the ratio between two failure probabilities in two different conditions (or components). This concept is utilized for design of different components of transmission lines (or various transmission lines) with different levels of reliability. In other words, some components of transmission lines can be designed for a higher level of reliability. Thus, the designer could be able to control the components failure sequence of the transmission line. It is generally recommended by the majority of design regulations and standards (such as ASCE-74 and IEC 60826) of power transmission lines that the foundation be designed more reliable than tower. In spite of this recommendation in the ASCE-74 loading guideline, no any specific value has been presented for this increase in reliability. Moreover, this parameter should be applied as an additional load factor in the foundation design process, which is chosen by the designer or owner of the transmission line.

The relative reliability factor (RRF) is defined to measure the reliability of two components or structures (such as tower and foundation) relative to each other. The RRF for tower and foundation can be defined as the following equation [35]:

$$RRF = \frac{P_{fT}}{P_{fF}} \tag{1}$$

Where P_{fT} and P_{fF} are annual failure probability of tower and foundation, respectively. The level of relative reliability can be adjusted by means of an appropriate return period for design loads or applying suitable safety factors in loads and strengths.

Another concept to control the failure sequence of components of transmission lines is called strength coordination recommended by IEC60826. According to this concept, some components in transmission lines must have more strength than others. For example, foundations must have more strength than towers. These concepts also can be used for development of design criteria for foundations in transmission lines according to IEC 60826, as indicated in the next section.

3- Calculation of safety factor for micropile geotechnical design in transmission lines subjected to compressive force

In order to determine the design safety factors of transmission line foundations and micropile based on the reliability concept, two general approaches can be adopted:

- Reliability-based: In this approach, the foundation design process is developed in a manner so that the reliability of foundation design is equal to a definite value (target reliability). In determination of safety factors based on this approach, the statistical characteristics of loads and strengths corresponding to the failure modes of foundation as well as the value of target reliability are required [35].

- Relative reliability-based: This approach deals with a foundation design process in which the reliability of foundation design is greater than that of tower with a certain amount. In order to determine the safety factors based on this approach, the statistical characteristics of tower ultimate capacity (as an input for foundation design) and the strengths corresponding to the failure modes of foundation and the value of foundation-tower relative reliability (RRF) are required [17].

In the current research, since most of the design standards of transmission lines (IEC 60826, ASCE 74 etc.) have emphasized on the higher values of foundation reliability or strength with respect to the tower, the relative reliability approach is selected for evaluation of safety factors. For implementation of this approach, the main relationship of micropile design for the ultimate limit state of compressive strength can be written as [34]:

$$F_{UN} \leq \frac{R_{U-FHWA}}{SF} \tag{2}$$

Where F_{UN} refer to micropile compressive force due to tower support reactions corresponding to tower nominal ultimate strength, $R_{U\text{-}FHWA}$ is nominal (or characteristic) compressive strength of micropile originated from the FHWA standard relationship considering the mean values of adhesive stress (α_{Bond}), and SF denotes the desired safety factor in this study.

3- 1- Relative reliability analysis in the micropile foundation of transmission towers

In order to calculate relative reliability factor (RRF) based on Equation 1, the failure probability of foundation and transmission tower need to be calculated using the following equations:

$$P_{fT} = P[F_{Tr} > R_T] = P[\ln(\frac{R_T}{F_{Tr}}) < 0] \tag{3}$$

$$P_{fF} = P[F_{Fn} > R_F] = P[\ln(\frac{R_F}{F_{Fn}}) < 0] \tag{4}$$

Where F_{Tr} and F_{Fn} are internal force in the critical member of tower and compressive force in micropile, respectively, both from an external loading condition (e.g. wind, ice, etc.). R_F is ultimate compressive strength of micropile, and R_T is tower ultimate strength (i.e. the internal force in the critical member corresponding to the tower ultimate strength at the moment of actual failure).

In this study, tower ultimate strength R_T is modeled as a lognormal random variable (See Section 3-2), and its calculation method is presented in section 3-2. The ultimate compressive strength of micropile R_F is also modeled as a lognormal random variable (see section 3-3). F_{Tr} is the extreme value (annual maxima) of load effect, and modeled as a random variable having extreme value type I (Gumble) probability distribution [17, 36], coefficient of variation (COV), and design characteristic (nominal) value F_{TrT} corresponding to return period T (mean annual exceedance rate equal to 1/T) as stated in section 3.4. F_{Fn} is modeled as a lognormal random variable that fully correlated with F_{Tr}. The main relationship of transmission tower design can be written as Equation 5 [35]:

$$\gamma_t F_{TrT} \leq R_{TN} \tag{5}$$

Where γ_t is the design load factor and is equal to one according to relevant transmission tower design standards (ASCE 74 and IEC 60826) and R_{TN} is the nominal (characteristic) value of tower ultimate strength. (i.e. the internal force in the critical member subjected to the nominal ultimate design loading table for conducting the type test of tower, and corresponding to the tower nominal ultimate strength).

Failure probabilities P_{fT} and P_{fF} can be calculated using reliability analysis methods such as Monte Carlo sampling, considering the limit state functions $g_1=\ln(R_T/F_{Tr})$ and $g_2=\ln(R_F/F_{Fn})$, respectively (see section 3.4).

Alternatively, in the context of strength coordination, exceedance probability of foundation strength with respect to tower could be written as [36]:

$$P_{SC} = P[R_F > F_U] = 1 - P[\Omega < 1] \tag{6}$$

Where P_{SC} is the exceedance probability, F_U is micropile compressive force due to the tower support reactions corresponding to the tower actual ultimate strength, and $\Omega=R_F/F_U$ is the strength ratio. F_U is modeled as a lognormal random variable that fully correlates with R_T. The exceedance probability P_{SC} can be calculated through determining the cumulative probability distribution (CDF) of Ω using Monte Carlo sampling method as stated in section 3.4.

3- 2- Probabilistic model of ultimate strength of transmission towers

To assess analytically the internal forces in tower members and reactions on foundation at the moment of tower failure, the following approaches can be adopted:

- Determining the mechanism of tower failure and corresponding ultimate load along with the support reactions using the nonlinear (or failure mechanism) analysis; and
- The use of tower internal forces and support reactions subjected to the design loads used in tower type test, which are increased by appropriate coefficients for taking the tower overstrength into account.

The application of the first approach is basically difficult and uncommon in engineering design. Alternatively, the second approach is the most applicable approach, in which the desired overstrength coefficient can be evaluated considering the statistical investigation of results for various towers based on large-scale type tests. On the basis of this approach, in order to calculate the statistical characteristics of tower ultimate strength R_T (and its reaction of foundation corresponding to the tower ultimate strength F_U) as a random variable, this parameter is defined as the product of a deterministic quantity, R_{TN} , and a random parameter, k_{Tr} as follows:

Where k_{Tr} denotes the random overstrength coefficient.

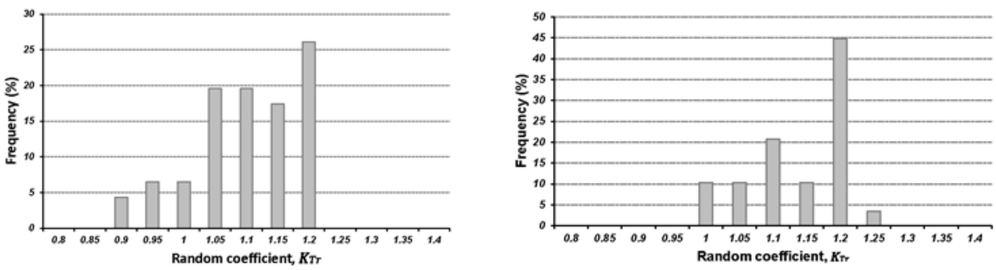
$$R_T = k_{Tr} R_{TN} \tag{7}$$

Loading test of transmission towers that also called "Type test", is generally set up to simulate and verify the most critical design conditions, adequacy of members and their connections. Full-scale type test of transmission tower is mandatory in transmission line engineering according to IEC 60652 standard. This kind of test should be done on a full size prototype lattice and pole tower subjected to static loads. The tested tower is fixed on the strong and rigid pad and the loads are applied to the connection points of the wire conductors to the cross arms. Loads are applied at different points on tower by remote controlled electric winches operated from the control room. To enable a horizontal loading on the tower, auxiliary structures are necessary. Applied loads are normally incremented to 50%, 90%, 95%, and 100% of the ultimate design loading pattern of tower and then, increased until failure (Figures 1a and b). When a premature failure occurs, all failed members are replaced and test is repeated after redesign of tower, until the tower is able to support the 100% ultimate design load [37, 38]. Consequently in the Equation 7, the deterministic quantity of tower strength is in fact the tower internal force subjected to the ultimate design loading pattern in the type test, and k_{Tr} is the ratio between the loading pattern at the moment of tower failure and the design loading pattern of the type test. This coefficient, which possesses different values, has been obtained in all the type tests of the transmission towers.

According to the statistics obtained from the type tests conducted on transmission towers at the Overhead-Line Structures Test Station of Niroo Research Institute (NRI-OSTS) in Arak city, the statistical distribution of tower collapse load coefficient frequency, k_{Tr}, has been displayed in Figures 2a and b, respectively for lattice and pole towers [NRI-OSTS Tower test reports, unpublished report]. In this investigation, 46 lattice towers and 29 pole towers have been tested. The mean value and coefficient of variation of k_{Tr} are 1.09 and 0.09 for lattice towers as well as 1.13 and 0.08 for pole towers, respectively. The linear trend in quantile-quantile (Q-Q) plot of collapse load coefficient (Figures 3), shows that the lognormal probability distribution is an appropriate estimation for probability distribution of k_{Tr}.

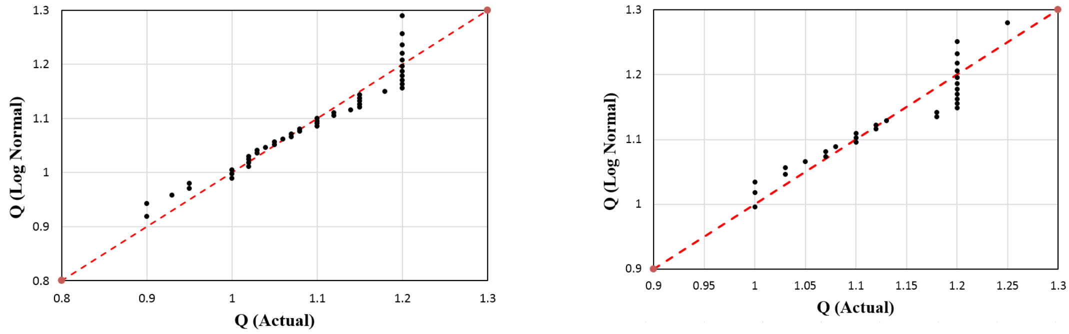
(a) NRI-OSTS tower test station in Arak city-Iran (b) Typical failure of lattice transmission tower in type test

Figure 1. Type test of full scale lattice Transmission tower in NRI test station



(a) lattice towers (b) Pole towers

Figure 2. Histogram of failure load coefficient (k_{Tr})



(a) lattice towers (b) Pole towers

Figure 3. Q-Q Plot of failure load coefficient (k_{Tr}) for lognormal probability distribution

3- 3- Probabilistic model of ultimate compressive strength of micropiles

In order to evaluate the statistical characteristics of ultimate compressive strength of micropile by using an approach similar to the tower, the value of ultimate strength is defined as the product of a deterministic quantity, $R_{U\text{-}FHWA}$, and a random parameter of K_{Fn} as:

$$R_F = k_{Fn}(R_{U-FHWA}) \tag{8}$$

Where R_F is ultimate compressive strength (obtained from experiment) of micropile, K_{Fn} is a random coefficient (the ratio between experimental and theoretical compressive strength of micropile), and $R_{U\text{-}FHWA}$ is nominal compressive strength achieved from the standard relationship of FHWA. Consequently, the statistical characteristics of ultimate compressive strength of micropile can be attained using the statistical analysis of K_{Fn} by considering the results of micropiles compressive tests.

In the current research, the results of the compressive tests conducted on 52 micropiles in various types of soil that reported in [39] based on [41, 42], have been used for statistical analysis. In this respect, a series of tests was carried out on micropile samples in dense sandy and clay-silt soils. Figures 4 and 5 displays the grain size distribution and the results of the standard penetration test (SPT) of a borehole nearby the implementation site of the micropiles respectively, for dense sandy soil [41].

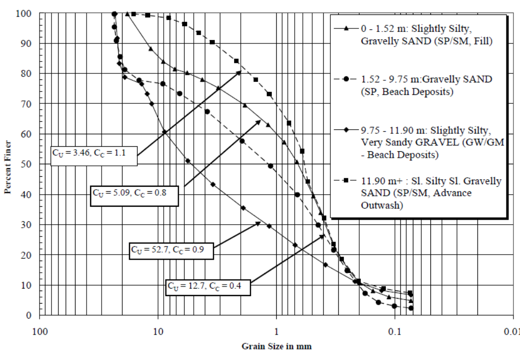


Figure 4. Grain size distribution for site subsurface [41]

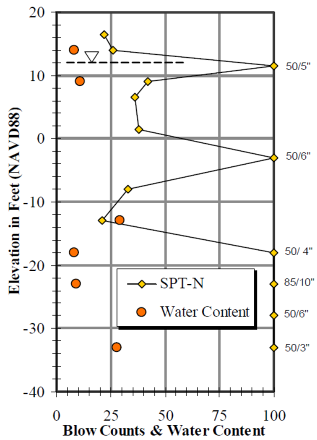


Figure 5. Results of SPT boring closest to tested micropiles [41]

The compression test in dense sandy soil was performed on micropiles with a cased zone of 3 m (10 foot) length and a 5.2 m (17 foot) long bond zone. The reaction piles included one sacrificial micropile and one adjacent production pile. To ensure that adequate reaction force would be available, both reaction piles had a bond zone lengthened to 7.6 m (25 feet). The reaction piles were spaced 1.2 m (4 feet) on-center from the test micropile. For the compression load test, a seating load of 53 kN (12kips) was applied prior to zeroing the dial gauges. Compressive load was applied in 5 cycles [41].

Table 1 and Figure 6 display the soil profile and properties and the results of field vane shear test (Cu) for clay-silt soils [42].

Table 1. Soil profile and properties [42]

Layer[a]	H (m)	w (%)	γ_{sat} (kN/m³)	e	PL	h	m_v (MPa⁻¹)	c (kPa)	Φ (°)
Top soil	1.0								
Lean clay crust (CL)	1.6	31.3	19.1	0.86	13.1	0.89	0.194	10	15
Soft lean clay (CL)	8.0	41.3-43.8	17.6	1.18-1.22	10.8-13	>1.00	0.321-0.360	7-9	12
Soft fat clay (CH)	>3.0	50.8	17.1	1.42	21.5	>1.00	0.417	10	9

Note: c, total cohesion determined by consolidated undrained (CU) triaxial tests; e, void ratio; H, thickness of soil layer; I_l, liquidity index; m_v, modulus of volume compressibility; PL, plastic limit; w, water content; γ_{sat}, saturated unit weight; Φ, total friction angle determined by CU triaxial tests. aTerminology follows Unified Soil Classification System

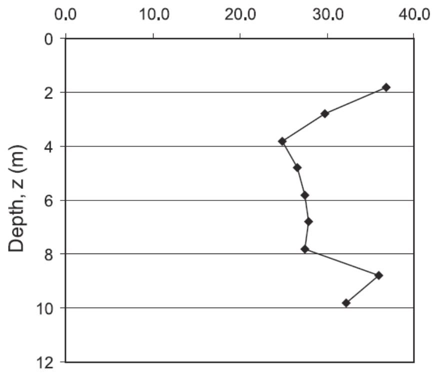


Figure 6. Field vane shear test results [42]

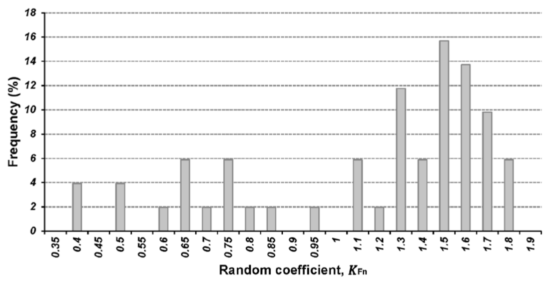


Figure 7. Histogram of the ratio between experimental and theoretical compressive strength of micropile (K_{Fn})

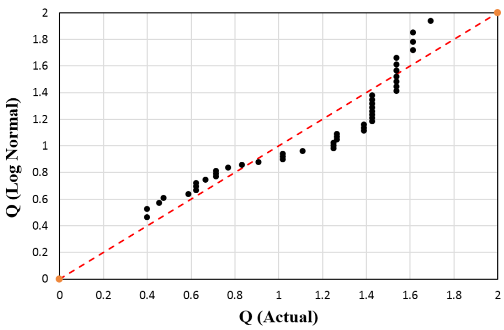


Figure 8. Q-Q Plot of micropile strength coefficient (K_{Fn}) for lognormal probability distribution

The compression test in clay-silt soil followed the American Society for Testing and Materials test standard ASTM D1143-81 (ASTM 1987) [42]. For both of soil types, according to the micropile classification method (based on type of grouting) recommended in the FHWA implementation manual [34], micropiles used in tests have been classified as type B and D with drilling method [41, 42].

Afterwards, the ultimate compressive strength (R_F) of these samples has been obtained using Davisson's limit method that according to [2, 43], this method is suitable adopted for analyzing the results of drilled piles tested. Moreover, the theoretical strength ($R_{U\text{-}FHWA}$) of each sample was calculated based on the common relationship and mean values of adhesive stress (α_{Bond}) presented in FHWA standard. In calculation of theoretical compressive strength, in the case of micropiles executed under the grouting pressure more than 1 MPa, the grouted zone diameter has been considered as 20 cm and 10 cm, respectively in sandy and clay soils.

Based on the tests results presented by [39], the statistical distribution of random coefficient frequency, K_{Fn}, is illustrated in Figure 7. The mean value and coefficient of variation of K_{Fn} are 1.20 and 0.42, respectively. Due to the variety existing in the test results, the coefficient of variation of K_{Fn} is relatively high. The linear trend in quantile-quantile (Q-Q) plot of coefficient K_{Fn} (Figure 8), shows that the lognormal probability distribution is a good estimation for probability distribution of K_{Fn}.

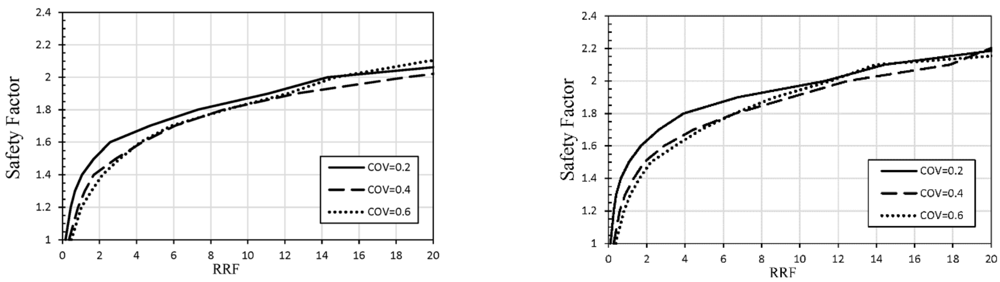
3- 4- Calculation of safety factor using the Monte Carlo sampling method

In this research, the design safety factors of micropiles in transmission line foundations were calculated using the Monte Carlo sampling method. Sampling techniques are one of the most common methods for analysis of reliability problems and calculating the failure probability; the most prominent of them is the Monte Carlo approach.

Failure probabilities P_{fT} and P_{fF} and resulting RRF (Equation 1) were calculated considering the limit state functions g_1=ln (R_T/F_{Tr}) and g_2=ln (R_F/F_{Fn}), respectively (based on Equations 3 and 4). Substituting Equations 5 and 7 into g_1, and 2 and 8 into g_2 lead to a relation between failure probabilities and random variables, assuming different values for desired safety factor. Correlated random variables for load effect (F_{Tr} and

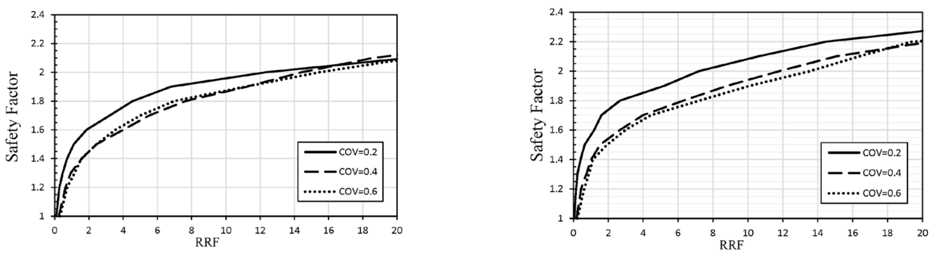
F_{Fn}) were generated considering the coefficient of variation (COV) in the range of 0.2 to 0.6 as typical values for climatic actions (IEC 60826) and design return period equal to 50, 150 and 500 years, corresponding to different reliability levels of transmission line, according to IEC 60826. Finally, the values of Limit state function and resulting RRF were calculated in terms of different values of safety factor.

The values of RRF are indicated in Figure 9 to 11 in terms of different values of safety factor, statistical characteristics of load effect (COV and return period T) and type of tower (Lattice or pole). In all cases, the safety factors are slightly higher for pole towers with respect to the lattice ones with identical RRF. As depicted in Figure 9-11, lower coefficients of variation (COV) and higher design return periods (T) for climatic actions lead to slightly higher value of safety factor for a specific RRF.



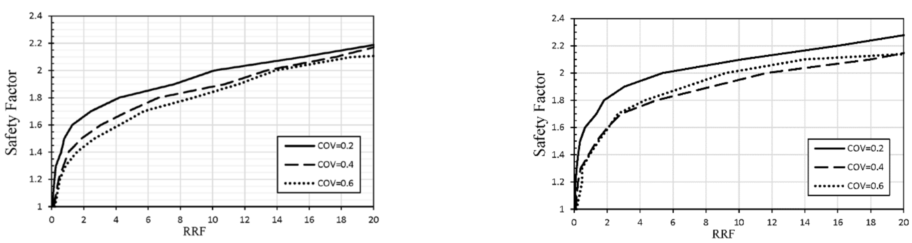
(a) lattice towers (b) Pole towers

Figure 9. Safety factor of micropiles compressive design with respect to RRF for T=50 Years



(a) lattice towers (b) Pole towers

Figure 10. Safety factor of micropiles compressive design with respect to RRF for T=150 Years



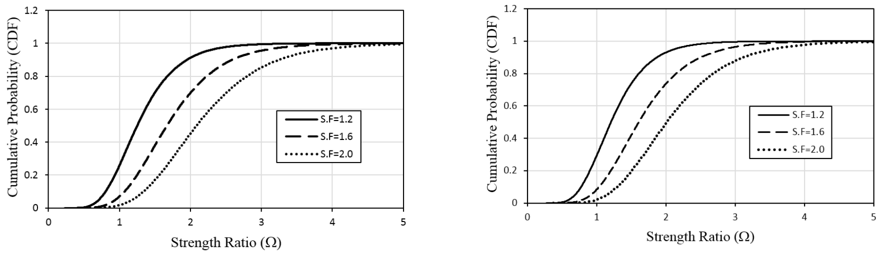
(a) lattice towers (b) Pole towers

Figure 11. Safety factor of micropiles compressive design with respect to RRF for T=500 Years

On the other hand, in the context of strength coordination (according to IEC 60826), the exceedance probability (P_{SC}) of foundation strength with respect to tower can be calculated based on Equation 6, considering Equations 7 and 8. The cumulative probability distribution (CDF) of Ω considering typical values of safety factor was calculated using Monte Carlo sampling method, and is shown in Figure 12a and b, respectively for lattice and pole towers. In fact, the value of CDF for Ω=1 is the complementary of P_{SC}. As depicted in Figure 12, using larger safety factors for micropile design result in larger strength ratios for specific exceedance probabilities of foundation strength with respect to tower. The safety factor could be determined using Figure 12, given desired value of P_{SC}. For example, based on Figure 12, to achieve P_{SC}=0.98 (or the value of CDF for Ω=1 is equal to 0.02), the safety factor of 2 should be used in micropile design. In this case, the value of strength ratio Ω has been less than 5 with the probability of 99.5%.

Tables 2 and 3 represents the values for P_{SC} and corresponding RRF for typical values of safety factor for lattice and pole towers, respectively. As shown in these tables, for a specific value of safety factor and exceedance probability (P_{SC}), different values have been attained for RRF, depending on the coefficient of variation and design return period of climatic load effects. This means that the design of foundation based on strength coordination (according to IEC 60826) does not lead to a unique RRF. This fact is more addressed in section 4.3.

As shown in Tables 2 and 3, the more the exceedance probability (P_{SC}) or RRF, the more the safety factor would be in the design process. Moreover, in all cases, the safety factor for pole towers are slightly greater than that for lattice towers, for a certain level of P_{SC} or RRF.



(a) lattice towers (b) Pole towers

Figure 12. Cumulative probability distribution (CDF) of strength ratio (Ω)

Table 2. Values of RRF and corresponding P_{SC} for lattice towers

Design Safety Factor	P_{SC} (%)	RRF								
		T=50 yr			T=150 yr			T=500 yr		
		COV= 0.2	COV= 0.4	COV= 0.6	COV= 0.2	COV= 0.4	COV= 0.6	COV= 0.2	COV= 0.4	COV= 0.6
1.2	74	0.44	0.84	1.02	0.27	0.63	0.73	0.17	0.43	0.52
1.6	93	2.59	4.33	4.23	1.86	4.01	3.55	1.29	3.06	4.23
2.0	98	14.29	18.52	14.71	12.33	14.41	14.45	10.09	13.33	13.89

Table 3. Values of RRF and corresponding P_{SC} for pole towers

Design Safety Factor	P_{SC} (%)	RRF								
		T=50 yr			T=150 yr			T=500 yr		
		COV= 0.2	COV= 0.4	COV= 0.6	COV= 0.2	COV= 0.4	COV= 0.6	COV= 0.2	COV= 0.4	COV= 0.6
1.2	71	0.28	0.59	0.80	0.15	0.44	0.61	0.09	0.24	0.48
1.6	92	1.69	2.91	3.49	1.18	2.67	2.98	0.66	2.03	2.09
2.0	98	11.32	12.48	11.61	7.20	11.80	13.56	5.36	11.67	9.20

4- Discussion

4- 1- Target value for RRF

In previous sections, using the relative reliability approach, the values of design safety factors of micropiles subjected to the compressive force were calculated and presented in terms of different relative reliability levels (RRF) and exceedance probabilities of foundation strength with respect to tower (P_{SC}) for the soil compressive failure.

One of the most important issues in reliability-based design of structures is the selection of desired level (or target level) of reliability, which is an economical optimization problem in nature. In the context of relative reliability, the target value for relative reliability factor (RRF) is needed to determine appropriate design safety factors. According to past studies, target annual reliability index for foundation of transmission lines has been recommended equal to β_t=3.2 for ultimate limit states, which corresponds to an annual failure probability equal to 0.07% (comprehensive report has been presented in [17]). Considering the target annual failure probability equal to 1% for transmission towers, the target value for RRF will be approximately equal to 14.

Alternatively, for simplification purposes in design of transmission lines, it is generally assumed that the failure probability of line (as a system) is approximately equal to suspension towers (as the weakest component of line system). This assumption is valid only if the failure probability of tower is larger enough relative to other components. In the case of foundation, the failure probability of tower-foundation as a series system is close to the failure probability of tower, provided the value of RRF would be large enough. The ratio of annual failure probability of tower-foundation system to tower (PR) has been shown in Figure 13 for lattice towers. As shown in this figure, dependent on the COV of climatic load effects, the RRF of tower and foundation should be larger than 8.5 to 11.5 in order for PR to be smaller than 1.05. Therefore, the target value of RRF=12 is appropriate for foundation design. As a result, the reliability of transmission line will be governed by its weakest component (suspension towers).

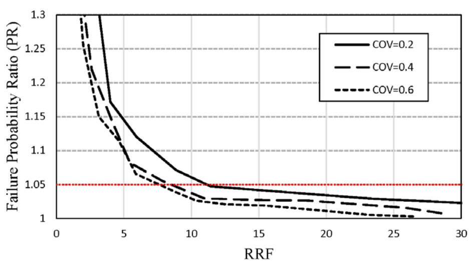


Figure 13. Relation between Failure Probability Ratio (PR) and RRF

4- 2- Calibration of safety factor corresponding with target RRF

For comparison purposes, the values of safety factors corresponding to the target RRF (=12) are represented in Table 4 with respect to the coefficient of variation (COV) and design return period (T) of load effect, based on Figures 9 to 11. In this table, the value of safety factors for geotechnical failure of micropiles subjected to compressive force has also been presented, which was extracted from FHWA standard. It should be mentioned that the approach adopted in FHWA is based on the allowable stress design method, and therefore, no any safety factor is applied to the loads. As can be observed in Table 4, the design safety factor for pole towers is slightly (up to 7.5%) higher than that for lattice ones. The average value of safety factor (in Table 4) for lattice and pole towers are slightly smaller and larger than those presented in FHWA, respectively (Up to 3% for lattice tower and 2% for pole tower). Considering the results of Table 4, applying the safety factor equal to 2.0 for lattice and 2.2 for pole towers in design process of micropiles (Equation 1) is recommended. Note that these safety factors are only valid for micropile design in dense sandy (SP-SM, SP&GW-GM) and clay-silt (SC, SM&SC-SM) soils, considering presented assumptions about bond strength (the average value from FHWA) and bond diameter (micropile diameter plus 20 cm and 10 cm, respectively in sandy and clay soils for pressure higher than 1 MPa). These safety factors are also close to the values recommended by FHWA. The failure mechanism, which were considered in annual failure probability is flexural buckling of angle members in cross arms, main body and legs for lattice towers; local buckling due to bending moment in bottom for pole towers and failure of bond between micropile and soil due to compression for micropile foundation.

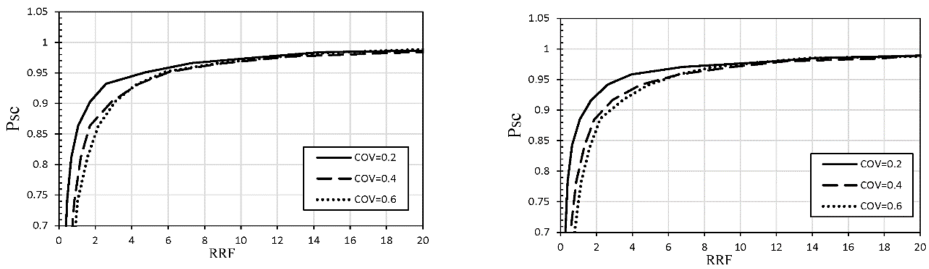
Table 4. Safety factors of micropiles geotechnical compressive design corresponding to RRF=12

COV	T=50 yr		T=150 yr		T=500 yr		Safety Factor (FHWA)
	Lattice	Pole	Lattice	Pole	Lattice	Pole	
0.2	1.93	2.03	2.00	2.13	2.05	2.14	2.0
0.4	1.90	2.03	1.93	2.00	1.95	2.05	
0.6	1.88	1.98	1.92	1.96	1.90	2.00	

4- 3- Relation between RRF and P_{SC}

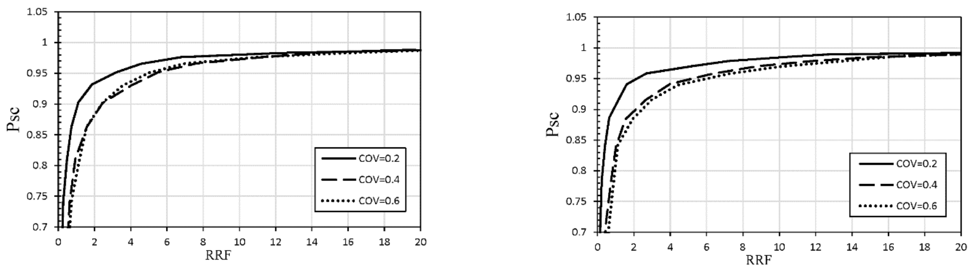
As mentioned in section 3.4, a particular level for strength coordination (P_{SC}) in foundation design would not necessarily lead to a unique amount of relative reliability (RRF). This is a weak point of transmission design based on strength coordination, according to IEC 60826. However, larger P_{SC} would correspond to higher level of relative reliability in general, but the value of RRF corresponding to specific values of P_{SC}, is dependent on the statistical specifications of load effect on tower. In Figures 14 to 16, the relation between P_{SC} and RRF has been presented for different values of coefficient of variation (COV) and return period (T) of external load effect. As shown in these figures, for a specific value of RRF, which is greater than about 10, the variation of P_{SC} with respect to COV and T has considerably been decreased. Specifically, for the target value of RRF (=12), the corresponding P_{SC} should be in the range between 0.97 and 0.99.

For design purposes, depending on the importance of transmission line and financial concerns, selecting the exceedance probability (P_{SC}) of foundation strength with respect to tower is the responsibility of designer and owner of the line. In other words, no any specific value is available for this parameter. In IEC 60826 standard, for coordinating the strength of different components of transmission line, the desirable value of exceedance probability has been considered as 90%. For micropile foundations, this value of P_{SC} would lead to an RRF between 0.65 and 3.0, which is not satisfactory for foundation design.



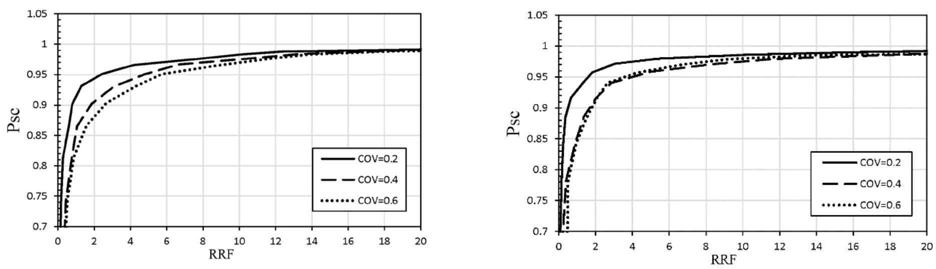
(a) lattice towers (b) Pole towers

Figure 14. Relation between exceedance probability (P_{SC}) with RRF for T=50 Years



(a) lattice towers (b) Pole towers

Figure 15. Relation between exceedance probability (P_{SC}) with RRF for T=150 Years



(a) lattice towers (b) Pole towers

Figure 16. Relation between exceedance probability (P_{SC}) with RRF for T=500 Years

5- Conclusions

In this paper, the design safety factors of micropile foundations subjected to the compressive force in geotechnical failure (of adhesion between micropile and soil) were determined for pole and lattice towers in power transmission lines using the relative reliability approach. On the basis of this approach, the design safety factor of micropile foundation is determined in a way so that the ratio of foundation reliability with respect to tower (or relative reliability factor, RRF) would be a certain value. Desired safety factors in terms of certain RRF were calculated using "Monte Carlo Sampling" method. The presented safety factors have been applied to the micropile compressive capacity, whose value can be calculated using the standard equation of FHWA (considering the mean values for micropile-soil adhesive stress). They are used in the design of micropile foundation accompanied by the tower support reactions due to the loads of type test design loading table. In addition to relative reliability, the concept of strength coordination that has been presented by IEC 60826 for design of transmission line components has also been examined in this research. Based on this approach, foundations should be designed to have more strength than towers and certain exceedance probability (P_{SC}). On the basis of the current research calculations and investigations, the following outcomes can be mentioned:

- Generally, considering a same level of relative reliability for pole and lattice towers, the design safety factor of micropile in the former is up to 7.5% higher than the latter.
- The target value of RRF=12 is appropriate for foundation design in transmission towers. Consequently, the reliability of tower-foundation as a series system will be governed by its weakest component (tower) which is a fundamental assumption in transmission line design (IEC 60826).
- Considering the target value of 12 for the relative reliability of foundation with respect to tower (RRF), the safety factor recommended in this study is 2.0 for lattice tower and 2.20 for pole tower. Difference between safety factors is due to different statistical characteristics of pole and lattice towers. These safety factors are only valid for micropile design in dense sandy (SP-SM, SP&GW-GM) and clay-silt (SC, SM&SC-SM) soils, considering assumptions about bond strength and diameter that present in this paper.
- For the target value of RRF (=12), calculated values of safety factor for lattice towers are slightly (average about 3%) smaller than that recommended by FHWA standard. On the other hand, safety factors for pole towers are slightly (average about 2%) higher than those in FHWA. Because of little deviation between results, it is recommended that SF=2.2 (or equivalently, the strength reduction factor α=0.45) has been used for all types of towers in engineering applications.
- In the context of strength coordination, a certain level for exceedance probability of foundation strength with respect to tower (P_{SC}) in foundation design would not necessarily lead to a unique amount of relative reliability. The target value of exceedance probability of foundation strength with respect to tower P_{SC}=0.9 proposed by IEC 60826 is not satisfactory, based on the current research, for micropile foundation design in transmission lines. This value should be at least 0.97.

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7- Nomenclature

COV Coefficient of variation
k_{Fnr} Random coefficient (ratio between experimental and theoretical compressive strength of micropile)
k_{Tr} Random coefficient (Tower overstrength)
F_{Fn} Compressive force in micropile, N
F_{Tr} Internal force in the critical member of tower, N
F_{TrT} Nominal internal force in the critical member of tower (corresponding to return period T), N
F_U Micropile compressive force due to the tower support reactions corresponding to the tower actual ultimate strength, N
F_{UN} Micropile compressive force due to tower support reactions corresponding to tower nominal ultimate strength, N
P_{fF} Annual failure probability of foundation
P_{fT} Annual failure probability of tower
P_{SC} Exceedance probability
R_F Ultimate compressive strength of micropile, N
R_T Tower ultimate strength, N
R_{TN} Nominal (characteristic) value of tower ultimate strength, N
$R_{U\text{-}FHWA}$ Nominal (or characteristic) compressive strength of micropile originated from the FHWA standard relationship, N
SF Micropile design safety factor

Greek symbols

α_{Bond} Adhesive stress, N/m2
β_t Target reliability index
Ω Strength ratio
γ_t Tower design load factor

References

[1] K. Ashouri, M. Dousti, A novel approach in execution of transmission lines with focus on decreasing the total cost, in: 22nd International Power System Conference, [In Persian] Iran, Tehran, 2007.

[2] A.-A. Zekavati, A. Khodaverdian, M.-A. Jafari, A. Hosseini, Investigating performance of micropiled raft in foundation of power transmission line towers in cohesive soil: experimental and numerical study, Canadian Geotechnical Journal, 55(3) (2017) 312-328.

[3] E. Abraham, C.H. Chen, P.L. Hlapcich, D.E. Johnson, N.W. Jufer, N.G. Salisbury, H. Shaw, Micropile transmission foundation in environmentally sensitive, challenging terrain, Deep Foundation Institute,2010.

[4] H.J. Wang, Research on micropile foundation of transmission tower on soft soil area, in: fifth International Conference on Civil, Architectural and Hydraulic Engineering (ICCAHE), 2016, pp. 574-579.

[5] K.K. Phoon, J. Ching, Risk and reliability in geotechnical engineering, CRC Press, 2014.

[6] K.K. Phoon, J.V. Retief, Reliability of geotechnical structures in ISO2394, in, CRC Press, 2016, pp. Chap. 5.

[7] G.B. Baecher, J.T. Christian, Reliability and statistics in geotechnical engineering, John Wiley & Sons, 2005.

[8] J.M. Duncan, Factors of safety and reliability in geotechnical engineering, Journal of geotechnical and geoenvironmental engineering, 126(4) (2000) 307-316.

[9] [9] T.M. Allen, Development of geotechnical resistance factors and downdrag load factors for LRFD foundation strength limit state design, in: US Department of Transportation, Federal Highway Administration, 2005.

[10] K.K. Phoon, Towards reliability-based design for geotechnical engineering, Special lecture for Korean Geotechnical Society, Seoul, 2004.

[11] Y.L. Zhao, W.G. An, Reliability-Based Stability Analysis of Foundation Pit Supported by Micro-Pile Composite Soil Nailing, in: Advanced Materials Research, Trans Tech Publ, 2011, pp. 2829-2833.

[12] Z. Luo, C.H. Juang, Efficient reliability-based design of drilled shafts in sand considering spatial variability, Journal of GeoEngineering, 7(2) (2012) 59-68.

[13] K. Phoon, J. Retief, J. Ching, M. Dithinde, T. Schweckendiek, Y. Wang, L. Zhang, Some observations on ISO2394: 2015 Annex D (Reliability of Geotechnical Structures) Structural Safety 62: 24-33 Crossref, Google Scholar, (2016).

[14] R. Jamshidi Chenari, R. Oloomi Dodaran, New method for estimation of the scale of fluctuation of geotechnical properties in natural deposits, Computational Methods in Civil Engineering, 1(1) (2010) 55-64.

[15] F. Nadim, Y.J. Choi, S. Lacasse, Calibration of partial safety factors for foundation design of offshore installations, in: Safety, Reliability, Risk and Life-Cycle Performance of Structures & Infrastructures, Taylor & Francis Group, London, 2013.

[16] J. Ching, K.-K. Phoon, Quantile value method versus design value method for calibration of reliability-based geotechnical codes, Structural Safety, 44 (2013) 47-58.

[17] K.K. Phoon, F.H. Kulhawy, M.D. Grigoriu, Reliability-based design of foundations for transmission line structures, EPRI Research Report TR-105000, Cornell University 1995.

[18] K.-K. Phoon, F.H. Kulhawy, M.D. Grigoriu, Reliability-based design for transmission line structure foundations, Computers and Geotechnics, 26(3) (2000) 169-185.

[19] K.K. Phoon, D.E. Becker, F.H. Kulhawy, Y. Honjo, N.K. Ovesen, S.R. Lo, Why consider reliability analysis for geotechnical limit state design, in: International Workshop on Limit State Design in Geotechnical Engineering Practice, 2003.

[20] K.-K. Phoon, F.H. Kulhawy, M.D. Grigoriu, Development of a reliability-based design framework for transmission line structure foundations, Journal of Geotechnical and Geoenvironmental Engineering, 129(9) (2003) 798-806.

[21] K.-K. Phoon, F.H. Kulhawy, M.D. Grigoriu, Multiple resistance factor design for shallow transmission line structure foundations, Journal of Geotechnical and Geoenvironmental Engineering, 129(9) (2003) 807-818.

[22] F.H. Kulhawy, K.K. Phoon, Observations of geotechnical reliability-based design development in North America, in: Foundation Design Codes and Soil Investigation in View of International Harmonization and Performance Based Design, IWS Kamakura, 2002, pp. 31-48.

[23] M.C. McVay, B. Birgisson, L. Zhang, A. Perez, S. Putcha, Load and resistance factor design (LRFD) for driven piles using dynamic methods—A Florida perspective, Geotechnical Testing Journal, 23(1) (2000) 55-66.

[24] S.G. Paikowsky, Load and resistance factor design (LRFD) for deep foundations, in: Foundation Design Codes and Soil Investigation in View of International Harmonization and Performance Based Design, IWS Kamakura, 2002, pp. 59-94.

[25] J. Zhang, L.-M. Zhang, W.H. Tang, Reliability based design of pile foundations considering both parameter and model uncertainties, Journal of GeoEngineering, 4(3) (2009) 119-127.

[26] K. Kwak, K.J. Kim, J. Huh, J.H. Lee, J.H. Park, Reliability-based calibration of resistance factors for static bearing capacity of driven steel pipe piles, Canadian Geotechnical Journal, 47(5) (2010) 528-538.

[27] H.-J. Kim, J.L. Mission, Probabilistic evaluation of economical factor of safety for the geotechnical design of pile axial load capacity, KSCE Journal of Civil Engineering, 15(7) (2011) 1167.

[28] D. Kim, M. Chung, K. Kwak, Resistance factor calculations for LRFD of axially loaded driven piles in sands, KSCE Journal of Civil Engineering, 15(7) (2011) 1185.

[29] J.H. Park, D. Kim, C.K. Chung, Implementation of Bayesian theory on LRFD of axially loaded driven piles, Computers and Geotechnics, 42 (2012) 73-80.

[30] J.H. Park, D. Kim, J.H. Lee, M. Chung, K. Kwak, LRFD implementation for static bearing capacity of driven piles, in: Safety, Reliability, Risk and Life-Cycle Performance of Structures & Infrastructures, Taylor & Francis Group, London, 2013.

[31] J. Jabo, Development of Reliability Based Design and Acceptance Protocol for Pile Foundations in Arkansas, GEO-RISK 2017, (2017) 277.

[32] F. Tonon, A. Mammino, Reliability-based design and construction issues for a micropile foundation in Costa Rica, Practice Periodical on Structural Design and Construction, 9(4) (2004) 227-236.

[33] A. Misra, L.A. Roberts, R. Oberoi, C.-H. Chen, Uncertainty analysis of micropile pullout based upon load test results, Journal of geotechnical and geoenvironmental engineering, 133(8) (2007) 1017-1025.

[34] FHWA, Micropile Design and Construction Guidelines, Federal Highway Administration, U.S Department of Transportation, U.S.A, 2005.

[35] C.J. Wong, Guidelines for Electrical Transmission Line Structural Loading, ASCE Task Committee on Structural Loading of the Committee on Electrical Transmission Structures, American Society of Civil Engineers, U.S.A, 2010.

[36] IEC, Design criteria of overhead transmission lines, in: CEI IEC 60826, CH-1211 Geneva 20, Switzerland, 2003.

[37] F. Paiva, J. Henriques, R.C. Barros, Review of Transmission Tower Testing Stations Around the World, Procedia Engineering, 57 (2013) 859-868.

[38] IEC, Loading tests on overhead line towers, in: CEI IEC 60652, CH-1211 Geneva 20, Switzerland, 2002.

[39] M.R. Ahmadi Golsefidi, F. Kalantari, Determination of bearing capacity and stiffness of micropiles using the loading tests results, in: 4th international Conference on Geotechnical Engineering and Soil Mechanics, [In Persian] Tehran, Iran, 2010.

[40] E. Ghannoum, Probabilistic design of transmission lines Part II: Design criteria corresponding to a target reliability, IEEE transactions on power apparatus and systems, (9) (1983) 3065-3079.

[41] A.W. Stuedlein, M.D. Gibson, G.E. Horvitz, Tension and compression micropile load tests in gravelly sand, in: 6th International Conference on case histories in Geotechnical engineering, VA, Arlington, 2008.

[42] J. Han, S.-L. Ye, A field study on the behavior of micropiles in clay under compression or tension, Canadian Geotechnical Journal, 43(1) (2006) 19-29.

[43] A.Y. Abd Elaziz, M.H. El Naggar, Geotechnical capacity of hollow-bar micropiles in cohesive soils, Canadian Geotechnical Journal, 51(10) (2014) 1123-1138.

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