LOAD AND RESISTANCE FACTOR DESIGN (LRFD) OF DEEP FOUNDATIONS USING A PERFORMANCE-BASED DESIGN APPROACH

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ABSTRACT

The Load and Resistance Factor Design (LRFD) methodology is being widely adopted for deep foundation design. The LRFD methodology can take many different forms depending upon the extent of the available data and the type of static capacity prediction models. This paper introduces a new performance-based design approach that incorporates the LRFD methodology. The application of this design approach is demonstrated for drilled displacement piles. Field load test data from drilled displacement piles installed at a single site is integrated within the developed approach to demonstrate a site specific reliability-based design methodology that satisfies performance-based requirements at both the strength and serviceability limit states. The *t-z* method is utilized along with Latin Hypercube sampling to calibrate LRFD resistance factors. The developed method reveals that design efficiency can be achieved simultaneously with safety in the design of deep foundation systems.

Key words: Performance-based design, LRFD, drilled displacement piles, resistance factors.

1. INTRODUCTION

The design of deep foundations has historically utilized static capacity equations to compute ultimate capacity. Design uncertainties, which are introduced from a number of sources, are managed by applying a global factor of safety to the computed ultimate capacity to assign an allowable capacity. One issue that arises with the use of static capacity methods is that a number of ultimate capacity magnitudes are possible depending on the technique. For example, methods such as the α-method, β-method, or O'Neill and Reese methods are extensively published techniques used to compute the ultimate capacity of a deep foundation (AASHTO 2007; Das 2007). In addition, the application of a global factor of safety to the design cannot explicitly account for the design uncertainties since the magnitude of the uncertainties is never actually quantified. Therefore, a design methodology that can eliminate bias in the ultimate capacity computations while ensuring efficient incorporation of design uncertainty is of utmost importance in the deep foundation industry.

This paper demonstrates the use of a site specific Load and Resistance Factor Design (LRFD) methodology for deep foundation systems within a new performance-based design approach. The developed approach incorporates a *t-z* model procedure for foundation capacity prediction, based on specific settlement performance criteria at both the strength and serviceability limit states, within a reliability-based design methodology. Field load test data from a series of drilled displacement test piles installed at a site are utilized for back-calculation of the *t-z* model parameters. The parameters are used to demonstrate how a site specific calibration method for resistance factors can be employed. The developed method reveals that design efficiency can be achieved simultaneously with safety in the design of drilled displacement piles, along with other types of deep foundation systems.

Manuscript received June 23, 2009; revised December 18, 2009; accepted December 21, 2009.

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2. THE *t-z* MODEL

Reliability-based design methods utilizing the *t-z* model approach have been described extensively in Misra and Roberts (2006), Misra *et al*. (2007a, b) and Roberts *et al*. (2008). In the *t-z* model approach, the soil-structure interaction at the side and tip of the deep foundation is represented by a series of non-linear springs. As the deep foundation is loaded, the springs will deform and the foundation will undergo settlement. With an increase in the load, the springs undergo yielding that begins at the top of the foundation and progresses to the tip. At some load, all of the springs will yield and the foundation will fail by plunging. The use of a *t-z* model approach allows for the development of a load-settlement curve that represents the behavior of the foundation over a wide range of loads.

Since the interface and tip soil resistance of the deep foundation element are modeled as springs, a strength and stiffness value for each spring must be assigned in the model. Along the soil-structure interface, each spring is defined by its initial tangent stiffness, K_{init}, and ultimate shear strength, τ_u, under drained or undrained conditions. The tip soil spring can be similarly represented with an initial tangent tip soil stiffness, K_{ti}, and ultimate strength of the tip soil, q_t, under drained or undrained conditions (Roberts *et al*. 2008). In most deep foundation applications, the site is not homogenous and thus the strength and stiffness parameters can vary along the length of the foundation and from one foundation to the next. This creates the need for a process that can efficiently handle uncertainties in the design.

The advantages of the *t-z* model approach over the conventional static foundation capacity methods are numerous. First, when utilizing a *t-z* model, the percentage of the applied load carried along the soil-structure interface and at the tip is computed explicitly based on the strength and stiffness characteristics of these components. Second, the *t-z* model is applicable to varying soil properties with multiple soil layers, and a variety of deep foundation systems and construction methods. Third, the *t-z* model permits easy integration of field load test data for verification of design assumptions. Fitting a load-settlement curve generated by the *t-z* model to field load test data will result in consistent back-calculation of the side and tip resistance which leads to increased prediction accuracy of deep foundation behavior and reduction in capacity bias. Last, although static capacity methods can provide a magnitude of the ultimate resistance of a deep foundation, it is quite possible that the ultimate resistance will be achieved at a settlement magnitude that would be detrimental to the operation of the structure. Using the *t-z* model with performance-based design criteria that are stated with respect to limiting tolerable deformations under various loading conditions as opposed to traditional force-based requirements (Foschi *et al*. 2002) will ensure that a structure can functionally operate within a desired tolerance throughout its lifetime. The determination of the limiting tolerable settlements can be assisted with FHWA (1982) or Zhang and Ng (2005) which report tolerable settlement for bridges and building structures, respectively.

3. LOAD AND RESISTANCE FACTOR DESIGN (LRFD)

The Load and Resistance Factor Design (LRFD) methodology is being widely adopted within the field of foundation engineering due to recently imposed requirements by the Federal Highway Administration (FHWA) in the United States. The incorporation of the LRFD methodology in the design of deep foundations is desired because the approach allows for explicit integration of design uncertainties into the overall process. It is known by practicing engineers that uncertainty exists in any design. Typical sources of uncertainty are inherent variability, measurement errors, and transformation uncertainty (Phoon *et al*. 1995). In addition, uncertainties from construction variability and model error can have large contributions. In typical deep foundation engineering, nominal values for the design soil parameters are utilized in a static capacity prediction model to determine the ultimate capacity of the foundation system. Design uncertainty is typically managed by assigning a global factor of safety to the calculated ultimate capacity of the foundation. Safety factors are usually assigned based on the design engineer's comfort level and without quantification of actual design uncertainty magnitudes (Kulhawy and Phoon 2006). This can lead to foundation designs that are overly conservative or designs that are potentially unsafe. Therefore, the systematic management of design uncertainties is a significant improvement over the global factor of safety method and will result in a safe, efficient, and consistent design of the deep foundation system.

Currently, the basis of the LRFD methodology in geotechnical engineering involves the probabilistic calibration of a parameter called a resistance factor. Resistance factors, with values less than or equal to 1.0, are applied to the calculated nominal resistance of the deep foundation, while load factors, with values greater than or equal to 1.0, are applied to the calculated loads. The following inequality must be satisfied in the LRFD approach:

$$\gamma_i \, Q_i \le \phi_R \, R \tag{1}$$

where, γ_i is a load factor, Q_i is a load, ϕ_R is a resistance factor and R is the nominal foundation resistance. Therefore, by rationally characterizing the magnitude of uncertainty in the deep foundation design, resistance factors are calibrated using statistical techniques and are intended to replace the currently utilized global factor of safety. In general, load factors have been extensively developed for structural design of bridges and other structures (Nowak 1995). It is thus critical to develop a reliable method to calibrate the resistance factor to ensure the design objectives of an LRFD approach are consistently satisfied.

Following the First Order, Second Moment method, the resistance factor, ϕ_R, can be computed as follows (Yoon and O'Neill 1997):

$$\phi_R = \frac{\lambda_R \left(\dfrac{\gamma_D \, E(Q_D)}{E(Q_L)} + \gamma_L \right) \sqrt{\dfrac{1 + \Omega_{QD}{}^2 + \Omega_{QL}{}^2}{1 + \Omega_R{}^2}}}{\left(\lambda_{QD} \, \dfrac{E(Q_D)}{E(Q_L)} + \lambda_{QL} \right) e^{\beta_T \sqrt{\ln\left[(1+\Omega_R{}^2)(1+\Omega_{QD}{}^2+\Omega_{QL}{}^2)\right]}}} \tag{2}$$

where, λ_R is the bias of the resistance, λ_{QD} and λ_{QL} are the bias of the dead load and live load, respectively, γ_D and γ_L are the load factors for the dead load and live load, respectively, Ω_{QD}, Ω_{QL}, Ω_R, are the coefficient of variation (COV) for the dead load, live load and resistance, respectively, $E(Q_D)$ and $E(Q_L)$ are the expected values of the dead and live load, respectively, and β_T is the target reliability index. In general, the values related to the loads in Eq. (2) have been extensively determined (see Baecher and Christian 2003). The ratio of the expected value of the dead load to the expected value of the live load does not significantly affect the value of the resistance factor and can be assigned a magnitude based on the characteristics of the structure. The target reliability index, β_T, relates the probability of failure of the deep foundation to an expected performance level. In deep foundation design, a β_T of between 2.0 and 3.5 is generally utilized (Kulhawy and Phoon 2006). Therefore, after assigning magnitudes to the known variables in Eq. (2), it is observed that the only unknown parameters are Ω_R and λ_R.

The aforementioned design uncertainties can be easily incorporated within the *t-z* model analysis approach. The observed uncertainty at a given site, based on either the site exploration process or field load test data, will directly affect the magnitude of the *t-z* model parameters. Therefore, the *t-z* model parameters are assumed as random variables and are defined with a nominal magnitude and COV. The COV of the model parameters must reflect the uncertainty caused by the variability within the soil and the construction process. The random behavior of the model parameters are assumed to follow a given cumulative distribution function (CDF), such as the normal or log-normal distribution. Once the uncertainty within the *t-z* model parameters is defined, Latin Hypercube sampling can be conducted. Latin Hypercube sampling allows for the random sampling of the *t-z* model parameters within the defined CDF at a specified number of equally probable intervals (Iman *et al*. 1981). The primary advantages of employing Latin Hypercube sampling over the conventional Monte Carlo simulation technique is that Latin Hypercube sampling: (1) does not require additional samples for an increased number of random variables; and (2) the random samples are taken one at a time, thus it is possible to systematically record which samples have been selected (Iman *et al*. 1981). The randomly selected values for each of the model parameters are then substituted into the *t-z* model analysis and a complete load-settlement curve is generated for that interval (*i.e.*, trial). The process is repeated with new random values for the *t-z* model parameters thereby resulting in a large number of load-settlement curves. The result of the Latin Hypercube sampling using the *t-z* model method is shown in Fig. 1. Figure 1 was developed for a 406 mm drilled displacement pile installed in medium-dense sand with an embedded length of 15 m. The COV of all *t-z* model parameters was assumed to be 0.30 for demonstration purposes. As observed in Fig. 1, the magnitude of variability in the load-settlement behavior of the drilled displacement piles installed at a site can be considerable. This has significant implications for the design of deep foundations, as additional efficiency in the design is possible by fully understanding the effect of the load-settlement curve shape. Therefore, by quantifying the variability in the deep foundation settlement, a logical process to calibrate a resistance factor, ϕ_R, using the generated load-settlement curves will be developed.

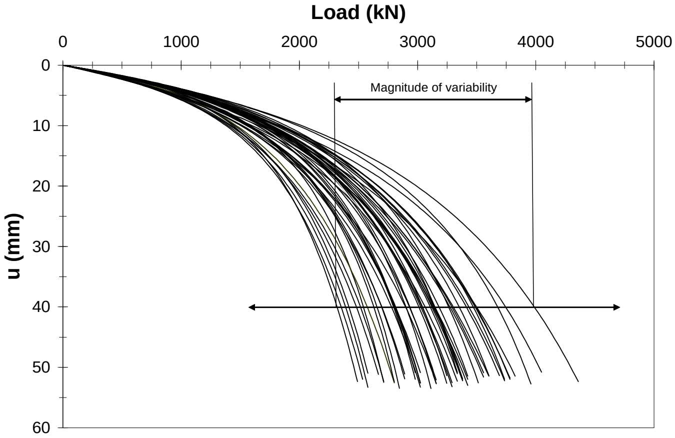

Fig. 1 Randomly generated load-settlement curves using Latin Hypercube sampling and *t-z* model approach

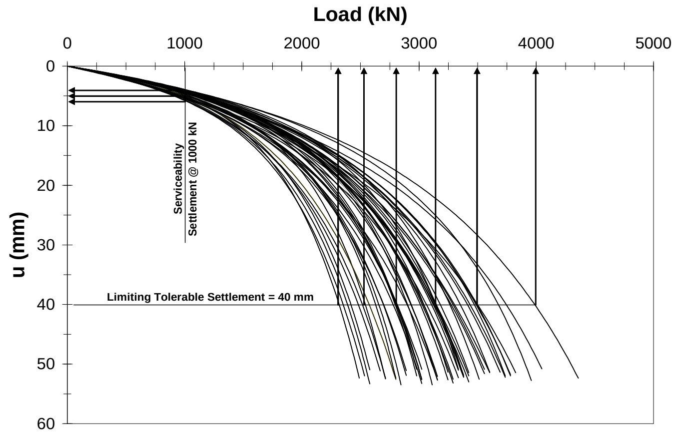

Fig. 2 Analysis of randomly generated load-settlement curves at the limiting tolerable settlement and at the service load

4. PERFORMANCE-BASED DESIGN USING *t-z* MODEL

In traditional deep foundation design, the ultimate capacity of the foundation is generally determined using a number of static capacity approaches. However, for deep foundations, the mere definition of "ultimate capacity" can be subjective. Deep foundations, when subjected to an increase in loading, will generally continue to settle until the magnitude of settlement becomes greater than what can be tolerated by the structure. Therefore, the use of a design approach at the strength limit state that incorporates a limiting tolerable settlement of the structure is justified. In addition, serviceability settlements, such as those that cause functionality problems with a structure, should be included in the overall design process. To that end, the analysis of *t-z* model generated load-settlement curves can be accomplished using two performance-based criteria: (1) a limiting tolerable settlement, which corresponds to a settlement under the factored load where the stresses within a structure become greater than the structural capacity; and (2) a serviceability settlement, which corresponds to a settlement under the service load where the functionality of a structure may be adversely affected.

From Fig. 2, it is observed that the analysis of the load-settlement curves results in a series of loads (*i.e.*, resistances), one from each randomly generated load-settlement curve, which correspond to the magnitude of the limiting tolerable settlement. The statistics of the resistances can be computed to develop a probability distribution function (PDF) of foundation resistance at the limiting tolerable settlement. It is additionally observed in Fig. 2 that the randomly generated load-settlement curves can be analyzed at the service load, which will result in a series of settlements that correspond to the service load. The statistics of the settlements can also be computed to develop a PDF of foundation settlement at the service load.

The statistics of the PDF for foundation resistance can be utilized to calibrate a resistance factor, ϕ_R, for design of the deep foundation at the Strength Limit State I (AASHTO 2007). The COV of the model parameters represents the variability of the foundation resistance at the limiting tolerable settlement and can thus be taken as Ω_R in Eq. (2). As will be further demonstrated, the *t-z* model can be utilized to reflect the actual load-settlement performance of the deep foundation in the field (*i.e.*, the *t-z* model can be employed to match the performance of actual field test data) and thus λ_R in Eq. (2) can be assumed to be equal to unity (Roberts 2008, Roberts *et al*. 2008, Roberts and Misra 2010). Once these values for Ω_R and λ_R are substituted into Eq. (2), the resistance factor for the Strength Limit State I can be computed. The factored resistance of the deep foundation is thus computed to be the nominal foundation resistance (*i.e.*, mean resistance from the foundation resistance PDF) corresponding to the limiting tolerable settlement multiplied by the calibrated resistance factor. The design of the deep foundation is thus satisfied if the factored resistance is greater than the factored load.

A statistical analysis can also be conducted using the PDF of settlement corresponding to the service load in order to satisfy the serviceability design criteria for the deep foundation. The service load is computed based on the load factors given in AASHTO (2007) for the Service Limit State I. Using the mean and COV of the settlement PDF, it is possible to compute the probability that the settlement at under the Service Limit State I will exceed the serviceability settlement that was specified as part of the design criteria. This probability of exceedance is essentially the area under the settlement PDF that is greater than the serviceability settlement. The probability of exceedance can be related to a reliability index, β, for convenience. The computed reliability index can be compared to a desirable reliability index that is selected by the design engineer and based on the importance of ensuring functionality of the structure. Thus the value of the desired reliability index can be wide ranging. If the probability of exceedance results in a value of β that is greater than the desired reliability index, the design of the deep foundation is satisfied at the Service Limit State I.

5. EXAMPLE OF THE PERFORMANCE-BASED LRFD APPROACH

A series of compression field load tests were conducted on drilled displacement piles at a site in Southern Alabama, USA. The site soils consisted of sandy silt and sandy clay. A narrow topographic depression originally resulted in a 4.5 m to 8 m elevation change across the site. This area had been undercut and filled at the time of test pile installation. Subsurface investigation consisted of augered borings and CPT soundings.

The design requirements specified a service load of 890 kN and a factored load of 1560 kN per pile. Based on structural considerations, the limiting tolerable settlement of an individual pile under the factored load was specified as 25 mm and the serviceability settlement of an individual pile under the service load was specified as 6.35 mm.

For each compression field load test, the data included head displacement versus applied load measurements, along with strain measurements from gauges placed at various depths within the pile. Figure 3 provides the recorded load-settlement curves from the drilled displacement pile load tests. The installed length of the field test piles varied. Five of the test piles had an installed length of approximately 16 m, two had an installed length of 12.5 m, and one had an installed length of 18.5 m. Four of the field test piles had a diameter of 356 mm, while the remaining had a diameter of 406 mm. The back-computation of the *t-z* model parameters followed the general procedure outlined in Roberts *et al*. (2008) using both the head settlement and strain gauge data from the field. In the back-computation process, the settlement performance of the *t-z* model is matched to the observed field settlement performance for each pile. To ensure proper strain compatibility, the strain gauge measurements from the field are matched to the strains in the *t-z* model as well. It should be noted that due to the construction technique for drilled displacement piles, the cross-sectional area of the pile can vary along the installed length. Therefore, using strain gauge measurements for back-computation of the *t-z* model parameters can be challenging since a constant pile cross-sectional area is typically assumed in design. A more detailed back-computation incorporating the drilled displacement load test data is presented elsewhere (Roberts *et al*. 2009). In this paper, the back-computation of the *t-z* model parameters using the strain gauge measurements focused on ensuring that the strain at the tip of the drilled displacement pile observed during the load test was within ±10% of the strain predicted by the *t-z* model using a constant cross-sectional area.

As observed from Fig. 3, the behavior of the load-settlement curves for the test piles is variable due to the aforementioned sources of uncertainty, along with geometric variances. Once the *t-z* model parameters were back-computed from each load test, the normal statistics of those parameters (mean and standard deviation) were calculated. The statistics of the parameters may not be considered robust due to the small number of load tests utilized in the back-computational process. However, Duncan (2000) and Allen *et al*. (2005) provide guidance for conducting a probabilistic calibration when the amount of data is small. Using the Three-Sigma Rule, the mean (*i.e.,* nominal value) and COV for each of the *t-z* model parameters was determined from the back-calculated field load test data and is summarized in Table 1. The COV of each model parameter is assumed to incorporate all the aforementioned sources of uncertainty at the given site. It should be noted that in some design situations, only one or two load tests, or possibly no load tests, will be conducted at a site. In these cases, the determination of the mean and COV of the model parameters must be based on in-situ site exploration and laboratory testing data. To that end, the development of a model parameter database for different deep foundation systems using field load test data appears to be warranted in order to assist in the determination of the mean of each model parameter on future projects with limited load testing. The determination of the COV of the model parameters using site exploration data can be aided with criteria given in AASHTO (2007). Some error in the estimation of the site uncertainty could result at sites where few to no load tests are conducted. However, in these cases, efficiency in the design may be less critical and thus slight over-estimation of the site uncertainty (*i.e.,* COV of the model parameters) is not necessarily detrimental to ensure adequate safety (see Roberts and Misra 2010).

The nominal values for the side and tip resistance parameters, along with the computed COV magnitudes and developed CDF for each *t-z* model parameter, were utilized in the Latin Hypercube sampling procedure. Each *t-z* model parameter CDF was divided into 1000 intervals, thus resulting in the random generation of 1000 load-settlement curves (Iman *et al*. 1981). Since different pile diameters and embedded lengths were tested in the field, it was determined to utilize the nominal parameters to develop a set of random load-settlement curves for 356 mm and 406 mm diameter piles with interaction zone lengths of 12 m

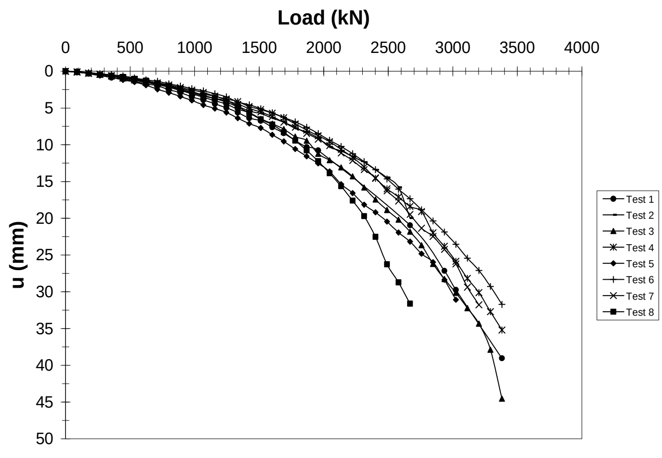

Fig. 3 Load-settlement curves for drilled displacement piles from field test data

Table 1 Nominal magnitude and COV of back-computed *t-z* model parameters

Model parameter	Nominal	COV
τ_u	180 kPa	7%
K	35 MPa	17%
E_s	160 MPa	23%
q_t	7 MPa	29%

and 18 m. To that end, 1000 load-settlement curves were generated for each diameter and interaction zone length combination. Once the load-settlement curves were randomly generated, it was possible to compute the nominal pile resistance from each load-settlement curve that corresponded to the specified limiting tolerable settlement. The COV of the nominal pile resistance (Ω_R) was calculated for each combination of diameter and interaction zone length. The bias of the nominal pile resistance (λ_R) was assumed as unity since the *t-z* model was employed to fit the field load test data for each pile. Finally, this information was substituted into Eq. (2) in order to calibrate a resistance factor for each design combination. In the resistance factor computations, the dead and live load factors were taken as 1.25 and 1.75, respectively. The COV and bias of the dead load was taken as 0.10 and 1.05, respectively, and the COV and bias of the live load was taken as 0.20 and 1.15, respectively. The target reliability index, β_T, was taken as 2.8, which corresponds to a probability of failure of approximately 0.2% for the Strength Limit State I. The resistance factor and factored resistance were computed for each combination of pile diameter and interaction zone length. The statistics of the pile head settlement at the service load were also computed in order to satisfy the Service Limit State I requirements. The pile head settlement statistics provide an indication of the variability within the pile head settlement under the service load. Based on these statistics, the probability that the pile head settlement will exceed the serviceability settlement of 6.35 mm, or probability of exceedance, was determined for each combination of pile diameter and interaction zone length. The results of the reliability-based design computations can be found in Table 2.

As observed from Table 2, the most efficient drilled displacement pile section for the site would be a pile with a diameter of 406 mm and interaction zone length of 12 m. It is observed that the factored resistance of this pile is 1690 kN, which is greater than the factored load of 1560 kN, and that the probability of exceedance at the service load is $2e^{-6}$%, which corresponds to a β greater than 5. The design computations demonstrate that the Strength Limit State I controls the design of the pile and suggest that it would be further possible to shorten the pile length and thus increase the design efficiency. Therefore, by conducting a performance-based design approach within the LRFD framework, it is shown that efficiency in the pile design was realized, while ensuring safety and the performance criteria were satisfied.

6. CONCLUSIONS

The Load and Resistance Factor Design (LRFD) approach is being widely adopted for deep foundation engineering in the United States. The implementation of the LRFD method requires the calibration of resistance factors that can rationally account for the uncertainty in the resistance of a deep foundation due to a number of sources. A method to calibrate resistance factors that can explicitly incorporate all known sources of uncertainty, while reducing model bias, is critical to ensure that deep foundation designs are safe and efficient.

The load-settlement analysis of the deep foundation system followed the *t-z* model methodology for soil-structure interaction. By introducing uncertainty into the *t-z* model parameters, a large number of load-settlement curves were randomly generated using the Latin Hypercube sampling technique. The load-settlement curves were analyzed using performance-based criteria specified for both the Strength Limit State I and Service Limit State I of the AASHTO code. The procedure allowed for concurrent deep foundation design at both limit states, while ensuring the performance criteria were satisfied.

A demonstration of the developed procedure was included to outline the flexibility and ease of the calibration technique. The demonstration included the analysis of load test data from a series of drilled displacement piles installed at a single site and resulted in a calibrated resistance factor that was site specific for design at the Strength Limit State I and a probability of exceedance for design at the Service Limit State I. It was observed that the utilization of the developed procedure within the LRFD framework would allow the engineer to assess the optimum pile for a particular site. The use of the LRFD approach has ensured that this optimum pile selection will result in a safe and consistent design throughout the site. Improved efficiency can ultimately save significant time and money on large foundation projects.

Table 2 Strength and service limit state design for drilled displacement piles

Pile diameter (mm)	Pile length (m)	Strength limit state pile resistance			Pile head settlement at service load		
		Nominal resistance (kN)	ϕ	Factored resistance (kN)	Nominal settlement (mm)	COV of pile head settlement	Probability of exceedance (6.35 mm)
356	12	2360	0.63	1490	4.1	0.10	7e–4%
	18	3160	0.63	1990	3.6	0.09	8e–11%
406	12	2690	0.63	1690	3.6	0.11	2e–6%
	18	3580	0.64	2290	3.0	0.09	1e–14%

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