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Reliability-Based Design of Proof Load Test Programs for Foundations

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ABSTRACT: There is currently an inconsistency in the recommendations that are available in pile design codes and practices regarding the required number of proof-load tests and the level of the proof loads. This paper presents the results of a comprehensive investigation that is conducted to study the effect of choosing different proof-load test programs on the reliability of piles. This is achieved by utilizing a Bayesian approach to update the capacity distribution of piles at a site given the results of the proof-load test program. In the updating exercise, an effort is made to update both the mean and the lower-bound capacity to maximize the benefit of the collected proof load data. The significance of the results presented lies in the fact that these results constitute necessary input to any practical decision framework for choosing the number and the magnitude of the proof load test that would maximize the value of information of the test program.

KEYWORDS: Proof loads, Reliability, Piles, Lower bound capacity, Bayesian updating

1. INTRODUCTION

Pile load tests have been long utilized in foundation engineering to reduce the uncertainties associated with pile capacity prediction. Generally, the foundation is sized based on an empirical design method using a reduced factor of safety (typically 2.0) provided that it passes a proof-load test up to twice the design load (ASTM D1153 1994). However, many international design codes and practices allow for the use of reduced factors of safety of different magnitudes, with the proposed factors of safety being dependent on the number and type of pile load tests that are conducted. Some common recommendations from international pile design codes are summarized in Table 1. These recommendations indicate variability in the correlation between the type and number of the specified pile load tests and the recommended reduced design factor of safety. In addition to the variability between the recommendations, a major drawback of any recommendation is that the designer does not have any indication of the inherent reliability/safety that is associated with the resulting design, since the recommendations are generally based on experience and are not associated with any robust reliability/risk analysis that supports their use.

Table 1 Worldwide Recommended Safety Factors for Static and Dynamic Pile Load Test Programs

Country	FS, No Load Tests	FS, with Static Tests	FS, with Dynamic Tests	Comments
USA, ASCE 1996	3	1.6 to 1.9	1.7 to 2	Design capacity is 0.4 to 1.0 MN.
Europe, EC7 2001	-	1.64	1.95	More than 5 Static, More than 20 Dynamic
Japan	3	2.7	2.7	-
Sweden 2000	-	-	2	If 25% of piles tested.
			1.6	If 100% of piles tested.

In the last decade, some research efforts have targeted analyzing the impact of proof-load tests on the design of foundations in the framework of a reliability analysis. Examples include the work of Zhang and Tang (2002), Zhang (2004), Su (2006), Najjar and Gilbert (2009a), and Park et al. (2011). Except for the study by Najjar and Gilbert (2009a), current reliability analyses focus on utilizing results from proof-load tests to update the mean or median of the capacity distribution. Results from these reliability analyses indicate that the magnitude of the proof load has to be higher than the mean capacity so that the updating process will have a significant effect on the reliability. As an example, Zhang (2004) recommends conducting 1 to 3 tests using proof loads that are larger than 1.5 times the predicted pile capacity (larger than 3 times the design load) so that the value of the test can be maximized.

Proof-load tests that are conducted up to 3 times the design load can be quite expensive and time consuming. In addition, the likelihood of failing the pile during the test increases significantly as the proof-load level increases. For geotechnical engineering applications, the left-hand tail of the capacity distribution governs the probability of failure since the uncertainty in the capacity is generally larger than the uncertainty in the load. As a result, the reliability of a foundation is expected to be strongly affected by the presence of a lower-bound capacity (Najjar and Gilbert 2009b). This is clearly shown in Figure 1 which illustrates the effect of a lower-bound capacity on the probability of failure for a typical foundation. The primary conclusion from Figure 1 is that a lower-bound capacity can have a significant effect on the calculated reliability. For example, consider a typical case where the factor of safety is 3.0. If the lower-bound capacity is anything greater than 0.6 of the median capacity, the probability of failure is reduced by more than an order of magnitude compared to the case where there is no lower bound.

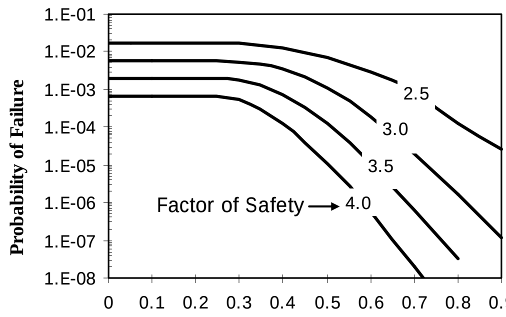

Figure 1 Effect of Lower Bound Capacity on Reliability

When a limited number of proof-load tests are conducted on a small percentage of foundations at a site, Bayesian techniques can be used to update the probability distribution of the foundation capacity at the site. In the updating process, the results of proof-load tests are typically used to update the middle of the capacity distribution (mean or median). However, Bayesian techniques have been also utilized to update the lower-bound capacity (rather than the mean capacity) at the tail of truncated capacity distributions. Najjar and Gilbert (2009a) proved through an illustrative example that running successful proof-load tests of relatively small magnitude (0.6 of the predicted capacity) on 3% of the piles at a site with 1000 piles resulted in a 30% reduction in the required median factor of safety while still maintaining the same level of reliability. The analysis assumes that all the piles survive the proof load tests and that the results of the load test program are used to update the lower-bound pile capacity.

This paper presents the results of a comprehensive investigation that is conducted to study the effect of choosing different proof-load test programs on the reliability of piles. This is achieved by utilizing a Bayesian approach to update the capacity distributions of piles given the results of the proof-load test program. In the updating exercise, both the mean and the lower-bound capacity are updated to maximize the benefit of the collected proof load data. The significance of the results presented lies in the fact that these results constitute necessary input to any practical decision framework for choosing the number of proof-load tests and the magnitude of the proof load that would maximize the value of information of the test program**.** What distinguishes the work presented in this paper from other studies in the literature is the incorporation of the lower-bound capacity in the reliability assessments, both in the prior and updated distributions of the pile capacity.

2. PROBABILISTIC MODEL FOR PILE CAPACITY

2.1 General Form

The main objective of the proposed study centers around updating the capacity distribution of piles at a site given results from a pile load testing program. In this study, the uncertainty in the pile capacity will be assumed to be modeled by a truncated lognormal distribution (Najjar 2005). The three parameters that define the pile capacity distribution are the mean capacity (r_{mean}), lower-bound capacity (r_{LB}) and the coefficient of variation (cov_R) as indicated in Figure 2. For simplicity, the coefficient of variation cov_R will be assumed to be a deterministic parameter that is generally evaluated for different pile capacity prediction models using databases of pile load tests (ex. Barker et al. 1991, Withiam et al. 1997, Goble 1999, Liang and Nawari 2000, McVay et al. 2000, 2002 and 2003, Zhang et al. 2001, Kuo et al. 2002, Kulhawy and Phoon 2002, Phoon et al. 2003a and 2003b, Honjo et al. 2003, Paikowsky 2003, Withiam 2003 and Gilbert et al. 2005). As an example, Gilbert et al. (2005) report cov_R values of 0.25 and 0.55 for the API (1993) method for driven steel pipe piles in clays and sands, respectively. Along the same lines, Zhang (2004) reports cov_R values ranging from 0.21 to 0.57 for about 14 methods of pile capacity prediction. On the other hand, the mean capacity (r_{mean}) and the lower-bound capacity (r_{LB}) will be assumed to be random variables (model parameters) with prior statistics that could be inferred from existing empirical models. The Bayesian updating tool which will be discussed in the next section will allow for updating either or both of the above 2 parameters (r_{mean} and r_{LB}) given the results of pile load tests.

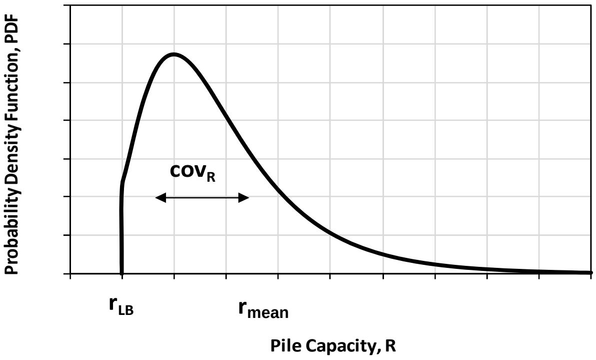

Figure 2 Parameters of Truncated Lognormal Capacity Distribution

2.2 Statistical Parameters of Prior Capacity Distribution

The prior statistics and probability distributions of the two parameters r_{mean} and r_{LB} were determined based on several realistic assumptions. First, both parameters were assumed to follow a lognormal distribution since both r_{mean} and r_{LB} cannot physically assume negative values. Second, it was assumed that the mean of r_{mean} could be estimated from databases of pile load tests as is conventionally done in evaluating the bias of pile capacity prediction models. The coefficient of variation of r_{mean} was assumed to be equal to 0.1 to account for systematic and random uncertainties in the determination of the soil properties at each test site in the database, uncertainties due to pile testing procedures and instrumentation, and uncertainties due to the interpretation of the pile capacity from the load-settlement curves of the pile load tests in the database.

With regards to the prior statistics of r_{LB}, it was assumed that the mean of r_{LB} is equal to about 0.5 of the mean of r_{mean}. This value is supported by the results presented in Gilbert et al. (2005) who show based on analyses of databases for driven piles in clays and sands that the ratio of the lower-bound capacity to the mean capacity for driven piles could range from 0.4 to 0.9, with an average of about 0.55 to 0.60. The lower-bound capacities are computed using physical models (ex. Najjar 2005 and Gilbert et al. 2005) and are not based on statistical minimum values of pile capacity. The prior coefficient of variation in r_{LB} was assumed to be equal to 0.2 (Najjar and Gilbert 2009b) to account for (1) uncertainty due to spatial variability in the soil properties needed in the estimation of the lower-bound capacity and (2) uncertainty in the models available for predicting the lower-bound capacity. Table 2 summarizes the statistical parameters used in the reliability assessments conducted in this paper. It is worth noting that the load, *s*, was assumed to follow a lognormal distribution with a coefficient of variation of 0.15 as is the convention. For comparison, the coefficients of variation specified by AASHTO (2004) to represent the uncertainty in bridge loads are 0.13 and 0.18 for the dead and live load respectively. For illustration and computational purposes, the mean load was assumed to take a value of 200 tons. A numerical estimate of the mean load is needed to illustrate the methodology presented in this paper for updating the pile capacity distribution using proof load tests. The results and conclusions will however be general and independent of the actual value of the mean load.

2.3 Simplified Probability Models for r_{mean} and r_{LB}

The model parameters to be updated based on proof-load test results are the mean and the lower-bound of the pile capacity at a given site. Given the mathematical complexities that are expected to exist in updating the probability density functions (PDFs) of r_{LB} and r_{mean}, a decision was made to model the two variables as discrete random variables rather than continuous variables. As a result, the lognormal distributions that model the uncertainties in r_{LB} and r_{mean} were replaced with probability mass functions (PMFs) that provided a simplified but accurate representation of the variation of the lognormal distribution. For each random variable, the range of values to be represented by the PMF was selected based on an analysis that ensured a mathematically adequate coverage of the probability density function. In general, the minimum value in the PMF was chosen to be that corresponding to the mean value minus 4 standard deviations while the maximum value was chosen to be equal to the mean plus about 10 to 20 standard deviations. Once the minimum and maximum values that define the range of the PMF were chosen, the range was divided into 44 equal intervals, resulting in a total of 45 values of r_{LB} or r_{mean} in the PMF. These numbers were chosen using trial and error to ensure that the simplification that is brought by replacing the PDF with a PMF does not compromise the accuracy in modeling the uncertainty in r_{LB} and r_{mean} for both the prior and the updated distributions.

Table 2 Statistics of Model Parameters

Design Parameter	Mean, μ	Coefficient of Variation, δ
Load, s	μ_s	0.15
Mean of Pile Capacity, r_{mean}	$FS.\mu_s$	0.1
Lower-Bound Pile Capacity, r_{LB}	$x.FS.\mu_s$	0.2
Coefficient of Variation of Pile Capacity, δ_r	0.4	-

Note: *FS* is the mean factor of safety (ratio of mean capacity to mean load) and *x* is the ratio of the mean lower-bound capacity to the mean of the mean pile capacity.

3. RELIABILITY OF PROOF-TESTED PILES

3.1 Updating the Parameters of the Capacity Distribution

When a limited number of proof-load tests are conducted on a small percentage of foundations at a site, Bayes' Theorem (Eq. 1) could be used to update the probability distribution of the model parameters for a given set of data such that:

$$f_{\vec{\Phi}|\vec{\varepsilon}}\left(\vec{\Phi}|\vec{\varepsilon}\right) = \frac{L\left(\vec{\varepsilon}|\vec{\Phi}\right) f_{\vec{\Phi}}\left(\vec{\Phi}\right)}{\int_{-\infty}^{+\infty} ... \int_{-\infty}^{+\infty} L\left(\vec{\varepsilon}|\vec{\Phi}\right) f_{\vec{\Phi}}\left(\vec{\Phi}\right) d\Phi_1 .. d\Phi_n} \tag{1}$$

where $f_{\vec{\Phi}|\vec{\varepsilon}}\left(\vec{\Phi}|\vec{\varepsilon}\right)$ and $f_{\vec{\Phi}}\left(\vec{\Phi}\right)$ are the updated (given the new data $\vec{\varepsilon}$) and prior joint distributions of the model parameters, $\vec{\Phi}$, $L\left(\vec{\varepsilon}|\vec{\Phi}\right)$ is the likelihood function, and $\int_{-\infty}^{+\infty} ... \int_{-\infty}^{+\infty} L\left(\vec{\varepsilon}|\vec{\Phi}\right) f_{\vec{\Phi}}\left(\vec{\Phi}\right) d\Phi_1 .. d\Phi_n$ is a normalizing constant.

One of the challenges associated with the use of Bayes' theorem within this framework is numerically finding a solution for the updated probability density function of the model parameters given the measured data. The decision to represent both the prior and updated distributions of the mean and lower bound capacities using probability mass functions was specifically made to tackle this challenge and to avoid high computational costs. This simplification significantly facilitates the solution of Equation 1. For illustration purposes, if "n" proof-load tests are conducted using a proof-load level r_{proof}, and if all the piles are able to withstand the proof load, the prior probability distribution of the lower-bound capacity can be updated such that:

$$P''_{r_{LB}}(r_{LB}) = \frac{\left(1 - \dfrac{\Phi\left(\dfrac{\ln r_{proof} - \lambda_R}{\zeta_R}\right) - \Phi\left(\dfrac{\ln r_{LB} - \lambda_R}{\zeta_R}\right)}{1 - \Phi\left(\dfrac{\ln r_{LB} - \lambda_R}{\zeta_R}\right)}\right)^n P'_{r_{LB}}(r_{LB})}{\sum_{i=1}^{m}\left(1 - \dfrac{\Phi\left(\dfrac{\ln r_{proof} - \lambda_R}{\zeta_R}\right) - \Phi\left(\dfrac{\ln r_{LB} - \lambda_R}{\zeta_R}\right)}{1 - \Phi\left(\dfrac{\ln r_{LB,i} - \lambda_R}{\zeta_R}\right)}\right)^n P'_{r_{LB}}(r_{LB,i})} \tag{2}$$

where $P''_{r_{LB}}(r_{LB})$ and $P'_{r_{LB}}(r_{LB})$ are the updated and prior lower-bound probability mass functions respectively and λ_R and ζ_R are the parameters of the lognormal distribution which are calculated as a function of r_{mean} and cov_R. The updated distribution of the lower-bound capacity is then used to calculate an updated estimate of the reliability of the foundations at the site. It should be noted that Equation (2) is only illustrative since it is assumed that r_{mean} is deterministic and r_{LB} is the random parameter that is being updated. In reality, r_{mean} in this paper is also assumed to be a random parameter that follows a given PMF. As a result, Equation 2 needs to be amended to take that into consideration by adding the contribution of all possible values of r_{mean} (in the likelihood function and in the normalizing constant) and weighing them by their respective probabilities (evaluated from the prior PMF of r_{mean}). The same principal is used to update r_{mean} instead of r_{LB} and in updating r_{median} and r_{LB} together.

A MATLAB algorithm was developed to automate the updating process and the calculation of the probability of failure and the reliability index. Using adaptive refinement, and as mentioned previously, a predetermined range of the PDF was selected to be represented by the PMF. Once the range of the random parameter was chosen, 45 equal intervals were selected within this range.

For the specific case that was considered in this paper, the mean load was chosen to be 200 tons, thus rendering a fixed interval width of approximately 20 tons for the mean of the capacity and about 15 tons for the lower bound capacity. The algorithm returns the updated PMF's and the corresponding probabilities of failure as output.

3.2 Formulation of the Reliability Problem

For the case where a truncated lognormal distribution is used to model the capacity, *r*, and a conventional lognormal capacity is used to model the load, *s*, the probability of failure p_f could be calculated:

$$p_f = \int_0^{\infty} \left(\frac{\Phi\left(\dfrac{\ln s - \lambda_R}{\zeta_R}\right) - \Phi\left(\dfrac{\ln r_{LB} - \lambda_R}{\zeta_R}\right)}{1 - \Phi\left(\dfrac{\ln r_{LB} - \lambda_R}{\zeta_R}\right)} \right) \left(\phi\left(\frac{\ln s - \lambda_S}{\zeta_S}\right) \frac{1}{s} \right) ds = \Phi(-\beta) \tag{3}$$

where Φ() is the standard normal cumulative distribution function, ϕ () is the standard normal probability density function, and β is the reliability index. The probability of failure in Equation (3) is for one combination of r_{LB} and r_{mean} and is calculated using numerical integration. For the case where r_{LB} and r_{mean} are random model parameters, the total probability of failure will be obtained using the theorem of total probability by incorporating all the probabilities of failure for all combinations of r_{LB} and r_{mean} and weighing them by the probabilities of each combination.

4. EFFECT OF TEST PROGRAM ON RELIABILITY

4.1 Updated Mean and Lower Bound of Pile Capacity

With the mathematical formulation devised in the previous sections, a systematic analysis could be conducted to investigate the effect of choosing alternative load test programs on the reliability of the pile design. In the analysis, the parameters that will be changed are: (1) the level of the proof load, r_{proof} (relative to the design load which is assumed as the mean load in this paper), (2) the number of proof load tests, and (3) the magnitude of the design factor of safety. To isolate the effect of the lower bound capacity from the mean capacity, the updating process for a given proposed load test program will first be conducted by updating the mean capacity only. The analysis is repeated for the case where the lower-bound capacity is updated only. Finally, the updating will be done for the two parameters simultaneously. This analysis will isolate the importance of the lower-bound capacity on the design of the piles at the site.

For illustration, it is assumed that the mean of the pile load in a given site is equal to 200 tons and that all other statistical parameters for *r* and *s* are in line with the values presented in Table 2. It was assumed that the ratio of the mean of r_{LB} to the mean of r_{mean} is equal to 0.5. With these assumptions, it could be shown that the required mean factor of safety would have to be around 3.0 to achieve a typical target reliability index of 3.0 for the piles at the site.

If proof load tests are to be conducted on a limited number of piles at the site, the required mean factor of safety could be reduced provided that the majority of the tests are successful. To illustrate this concept, it is assumed that 15 statistically independent proof load tests of up to 2 times the design load (assumed to be the mean load) are conducted on 15 piles that are designed and constructed at a reduced mean factor of safety of 2. If the tests were successful, the results of the load test program could be used to update the capacity distribution of the piles at the site. This is illustrated in Figures 3a, 3b, and 3c where the results of the testing program are used to update the probability mass functions of the mean capacity alone, the lower-bound capacity alone, and the joint PMF of the mean and the lower bound capacity, respectively. Results in Figure 3 indicate that the impact of the successful proof load tests is to shift the distributions of both the mean capacity and the lower-bound capacity to the right. In other words, the probabilities of relatively low values of the mean and lower-bound capacities decrease, while the probabilities of the higher values increase as a result of the updating process. The shifting of the mean and the lower-bound capacity to the right is expected to translate into improvements in the reliability index and reductions in the probabilities of failure of the piles at the site, thus allowing for the utilization of lower factors of safety for a given level of reliability.

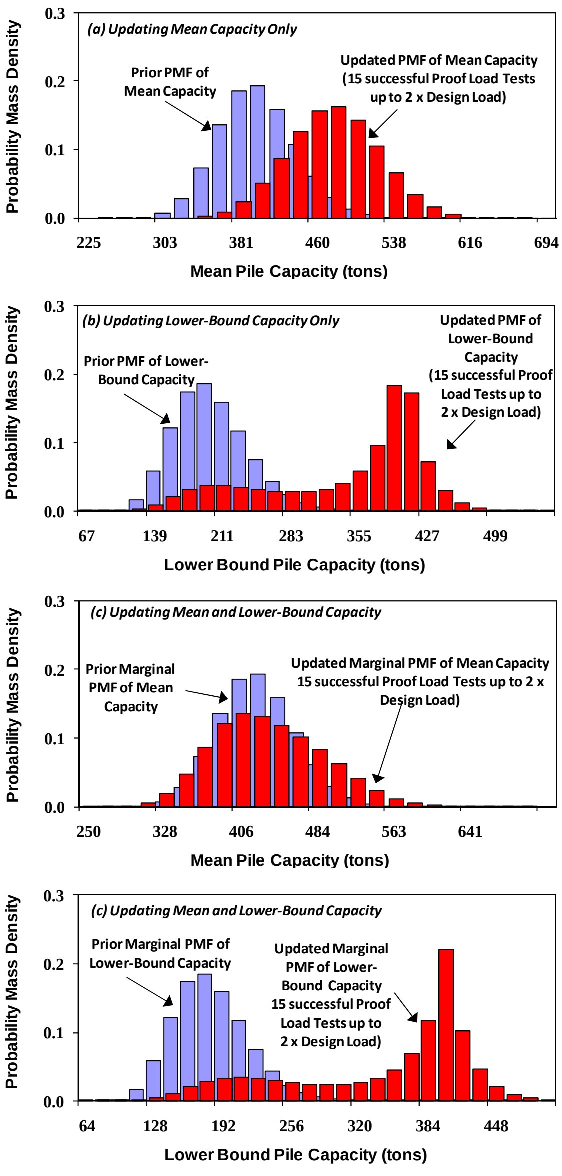

Figure 3 Updating the Probability Mass Functions of r_{mean} and r_{LB} (15 proof load tests, r_{proof} = 2 x Design Load, FS_{mean} = 2.0)

Further analysis of the data on Figure 3 indicates that when the updating process is conducted on the joint PMF of r_{mean} and r_{LB}, the major thrust of the updating process is on updating the lower-bound capacity rather than the mean. This observation could be explained by two facts. First, the uncertainty in the prior distribution of r_{LB} ($\delta_{r,LB}$=0.2) is larger than the uncertainty in the prior distribution of r_{mean} ($\delta_{r,mean}$ =0.1). This makes the lower-bound capacity a more favorable parameter for updating. Second, the likelihood function in Equations 1 and 2 is expected to be more sensitive to changes in the lower-bound capacity (clearly illustrated in Figure 1) than the mean capacity, particularly for values of r_{LB} that exceed 0.4 to 0.5 of the mean capacity, as is the case in this problem.

4.2 Updated Pile Reliability for FS_{mean} = 2.0

For the case considered in Figure 3, the mean design factor of safety was assumed to be equal to 2.0. For the prior scenario (assuming no load tests are conducted), this relatively low factor of safety results in a relatively small and virtually unacceptable reliability index that is slightly less than 1.9. When 15 successful proof load tests with r_{proof} equal to twice the design load are conducted, the distribution of pile capacity at the site is updated through the PMFs of r_{mean} and r_{LB} as indicated in Figure 3. The positive effect of the updating process is reflected in improved values of the reliability index as indicated in Figure 4. For the specific case of the 15 proof load tests that are conducted to twice the design load and assuming a factor of safety of 2.0, results on Figure 4 indicate that the reliability index increases from its prior value of 1.9 to values of about 2.2, 2.55, and 2.85 for cases where the mean capacity is updated alone, the lower-bound capacity is updated alone, and both the mean and the lower-bound capacity are updated together, respectively.

The variation of the reliability index with the number of proof load tests for different proof load levels is presented in Figure 4. Results on Figure 4 indicate that the effect of almost all the proof load test programs is to increase the reliability compared to the case where no proof load tests are conducted. As expected, the reliability index generally increases as the number of proof load tests increases and as the proof-load level increases. Results on Figure 4a indicate that utilizing the results of the proof load tests to update r_{mean}, results in relatively small increases in the reliability index. For example, the reliability index increases from around 1.9 (for the case where no proof tests are conducted) to a maximum of about 3.0 for the case where 30 tests are conducted to up to 3 times the design load.

On the other hand, results on Figure 4b indicate that updating the lower-bound capacity results in significant increases in the reliability index, with maximum values exceeding 6 for the largest number of tests and the highest proof load levels. These results are significant because they indicate that for the probabilistic model of the pile capacity that was adopted in this paper, the results of a proof load testing program could be more efficient at updating the lower-bound capacity than the mean capacity. The results on Figure 4c where the proof load tests were used to update the joint PMF of the mean and lower-bound capacity confirm this observation since the updated marginal PMFs indicate that the lower-bound capacity governed the reliability index since it was the most affected by the updating process compared to the mean capacity (see Figure 4c).

A general comparison between the results on Figures 4b and 4c indicates that updating r_{mean} and r_{LB} together (Figure 4c) generally results in slightly higher values of the reliability index compared to the case where only r_{LB} is updated. However, this observation is reversed for the few cases where the calculated reliability index was very large (generally greater than 4.0), where higher reliability indices were calculated for the case where only r_{LB} was updated. From a physical standpoint, this observation might not be logical and is expected to be attributed to inaccuracies in the numerical computations and assumptions which could only be evident at such small values of the probability of failure and which are not expected to be relevant at typical target risk levels for foundation design (target reliability indices ~ 3.0).

4.3 Factor of Safety vs Reliability for Different Test Programs

Since the main objective of this paper is to study the effect of choosing different proof-load test programs on the required factor of safety for piles, the target factor of safety needed to achieve target reliability indices of 2.5, 3.0, and 3.5 for the different proof load testing programs considered in this study was calculated and plotted in Figures 5a, 5b, and 5c, respectively. The results in Figure 5 show that different combinations of factor of safety, proof load level, and number of proof load tests could be selected to achieve the desired level of reliability.

For the most common case where the target reliability index is generally taken as 3.0, Results on Figure 5b indicate that designers have the option of choosing test programs that are based on a few number of load tests that are conducted to a relatively high proof load level or load tests that include larger number of proof tests that are conducted to a relatively smaller proof load level. As an extreme case, one could choose a relatively large factor of safety (approximately 3) without conducting any proof load tests. On the other extreme, one can choose a relatively aggressive load testing program (ex. 12 tests up to 3 times the design load) to minimize the factor of safety to a value of 2.0. Alternatively, the same reduced factor of safety of 2.0 could be achieved with a smaller proof load level (1.5 x design load) but with a larger number of tests (27 tests).

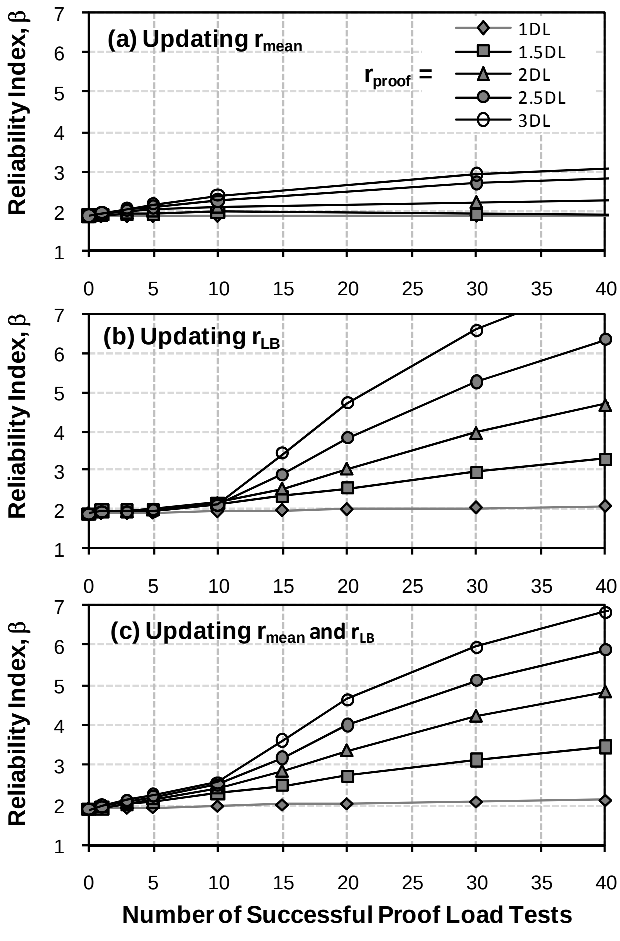

Figure 4 Effect of Load Test Program on the Reliability of Pile Design (FS_{mean}= 2)

For cases involving foundation systems that are redundant (example, large pile groups), it has been shown that the added redundancy allows for reducing the target reliability index of the individual foundation without compromising the reliability of the foundation system. For a reduced reliability index of about 2.5, results on Figure 5a indicate that no load tests are required to achieve the target reliability index if mean factors of safety that are greater than 2.5 are adopted. However, further reduction in the required factor of safety could be achieved with proof load testing. For example, the factor of safety could be reduced to 2.0 by running 9 tests up to 3 times the design load, or 15 tests up to 1.5 times the design load.

For cases where the desired level of reliability is required to be higher than the typical acceptable reliability levels (example, sensitive structures, heavily loaded foundations with no redundancy, etc.), reliability indices that are in excess of 3.0 may be desired. Results on Figure 5c indicate that if a target reliability level of 3.5 is desired, the required number of proof load tests and the level of the proof loads will need to be higher compared to the previous cases where the reliability index was lower. As an example, one possible design scenario could involve the use of a factor of safety of 3.0. To achieve the desired reliability level with this design scenario, the designer has the option of using a test program consisting of 5 load tests up to 3 times the design load or 21 load tests up to 1.5 times the design load. Another design scenario could consist of using a reduced factor of safety of 2.0. In this scenario, the designer could choose a program consisting of 15 tests conducted up to 3 times the design load or 43 tests conducted up to 1.5 times the design load. Other combinations of design scenarios and load testing programs could also be selected to achieve the same reliability level.

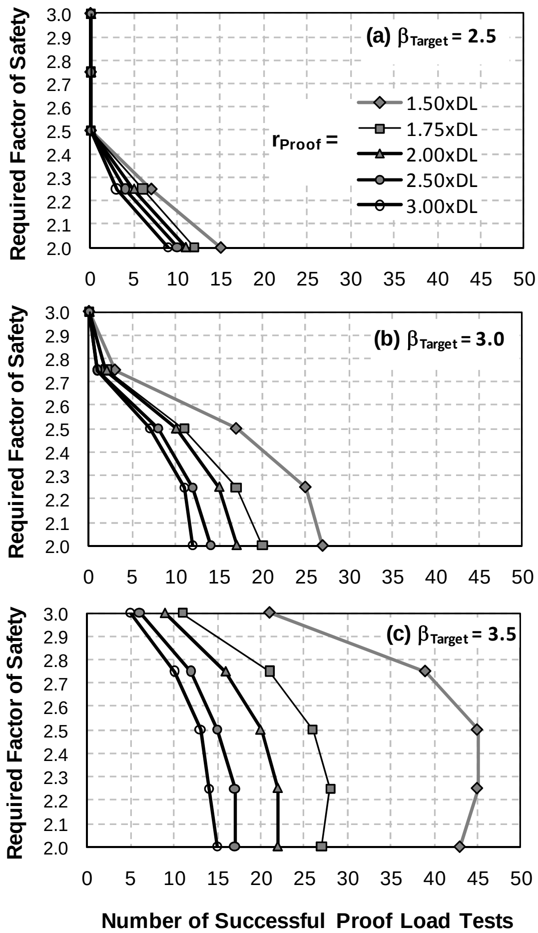

Figure 5 Required Factor of Safety to Achieve a Target Reliability Level of β = 3.0 for different Load Testing Programs

4.4 Effect of Failures on the Updated Reliability

In all the results and observations presented in the previous sections of this paper, it was assumed that all the tested piles survived the proof load tests. In reality, a proof load testing program could witness a number of foundation failures during its implementation.

The impact of these failures could be incorporated in the updating methodology presented in this paper by modifying the likelihood function to reflect both survivals and failures. When a number of piles fail during a proof load test program, the updated probability of failure is expected to increase compared to the case where all the piles survive the proof tests. With a large percentage of failed piles, the updated distributions of the mean pile capacity and lower-bound capacity could shift to the left, resulting in updated probabilities of failure that are even greater than the prior probability of failure (Zhang, 2004).

To investigate the impact of failures on the updated reliability of the pile design, an analysis was conducted whereby several design scenarios (as reflected in the assumed mean factor of safety), several proof load testing programs (as reflected in the number of proof load tests), and several alternatives for the results of the proof load tests (as reflected in the number of failed piles) were considered. The mean factor of safety was varied from 2.0 to 3.0 and the updated reliability indices for test programs involving 5, 10, 20, and 30 proof load tests that are conducted up to twice the design load was calculated. For each proof load test program considered, the analysis was conducted for the cases where no failure occurred and for 5 other cases whereby a certain percentage of the test piles was assumed to have failed. The reliability indices that are associated with these cases are presented in Figure 6 together with the reliability indices of the base case whereby no test program is implemented at the test site.

A thorough analysis of the results on Figure 6 lead to several interesting observations: (1) as expected, for a given design scenario and a given proof load test program, the updated reliability index was found to decrease as the percentage of failed piles increase, (2) the magnitude of the relative decrease in the updated reliability index seems to decrease as the number of failed piles increase, (3) the design scenarios that involve relatively large factors of safety generally suffer the most from the negative impact of the pile failures, and (4) the percentage of failed piles that seem to result in an updated reliability index that is almost equal to the prior reliability index (i.e., the proof load test program becomes inefficient) seems to be in the range of 30 to 40% of the tested piles.

The above observations are significant in that they shed light on the impact of failures of proof-load tested piles on the updated reliability of the pile design. In the design phase of a project, and before the proof-load testing program is established, a designer has to consider all the possible scenarios that could occur with regards to the possible results of the proof load test program. The likelihood of occurrence of each possible test result could be evaluated using the prior distribution of the pile capacity at the site. These likelihoods could be combined with the calculated updated reliability indices for the different test scenarios and utilized within a decision making framework at the design stage of the project to establish the load test program that would maximize the value of information of the test program.

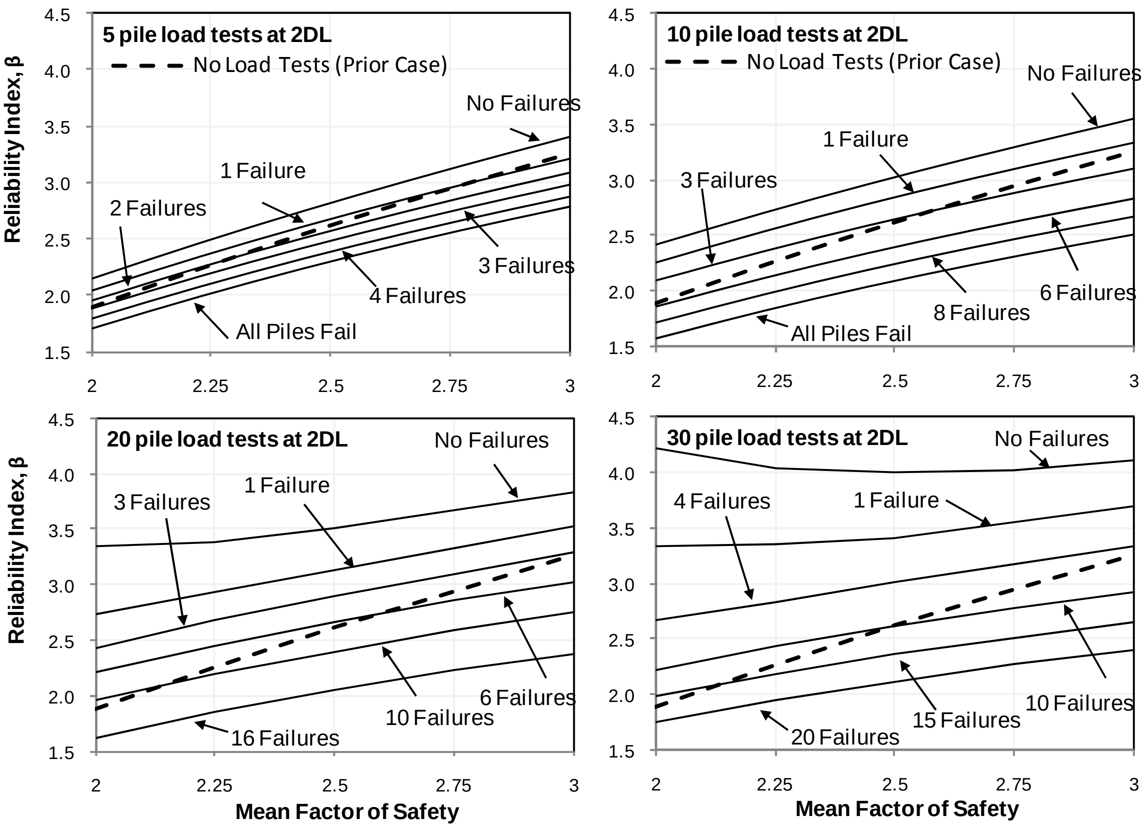

Figure 6 Effects of Pile Failures on the Updated Reliability Index

5. CONCLUSIONS

Based on the results of a load-test program, the use of lower factors of safety can be justified for the final foundation design. A less conservative design results in savings in installation costs and material costs. The cost of conducting load tests with large proof loads can be very high. As such, less conservatism in the design can be achieved with test programs where a larger number of piles are tested to relatively small proof-load levels. The example design scenarios that were presented in this paper illustrate this concept. A decision analysis that incorporates alternative load-test programs can be conducted in the design phase of a project to provide a basis for choosing the number of proof-load tests and the magnitude of the proof load that would maximize the value of information of the test program.

Based on a comprehensive assessment that was conducted in this paper with regard to the impact of choosing different proof load testing programs on the design of piles, the following conclusions can be made:

1. There is a current and pressing need for establishing simple but realistic methodologies for designing proof load test programs for piles and associating these programs with decisions regarding the required design factors of safety. This need is present at the design stage of a project and should be addressed for different levels of reliability.
2. The Bayesian updating approach, coupled with some simplifications regarding the probabilistic modeling of the pile capacity distribution, could provide a realistic framework for satisfying the above need.
3. The use of a truncated lognormal distribution that could incorporate the existence of a physical lower-bound pile capacity adds a realistic component to the pile capacity model and makes the updating process more flexible. The flexibility results from the fact that the data that is collected during the proof load testing program could be used to update the mean capacity (as is the convention) in addition to the lower-bound capacity.
4. In general, the impact of conducting a number of successful proof load tests is to shift the distributions of the mean capacity and lower-bound capacity to the right, resulting in an improved reliability index and a reduced probability of failure. The impact of the proof load tests increases as the number of proof-tested piles increase and as the level of the proof-load tests increase. In addition, the higher the required target level of reliability, the more the successful tests that are needed and the higher the associated safety factors.
5. The positive impact of proof-load test programs was found to decrease when the results indicated a number of failed piles. The percentage of failed piles that seem to result in an updated reliability index that is almost equal to the prior reliability index (i.e., the proof load test program becomes inefficient) seems to be in the range of 30 to 40% of the tested piles.

It should be noted that the results presented in this paper are based on several assumptions that were made with regards to the general form of the probability distribution of the pile capacity and to the statistics associated with this probability distribution. A major assumption is related to the fact that the coefficient of variation of the pile capacity was assumed to be constant (0.4) and was not updated in the analysis. Another major assumption is related to the fact that the ratio of the mean lower-bound capacity to the mean of the mean capacity was assumed to be 0.5. Although these assumptions are realistic and representative of many pile design scenarios, there could be cases where the coefficient of variation of the capacity is greater or less than 0.4, and cases where the ratio of the lower bound to the mean capacity could be greater and less than 0.5. The results presented in this paper could be affected by these assumptions.

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