ISGSR2007 First International Symposium on Geotechnical Safety & Risk
Oct. 18~19, 2007 Shanghai
Tongji University, China

Reliability evaluation of bored piles with multiple defects

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ABSTRACT:This paper aims to propose a methodology to quantitatively evaluate the reliability of pile foundations considering the possibility of multiple pile defects presence. The probability of failure of the pile considering the possibility of multiple defects presence is formulated by integrating the probabilities of failure for an intact pile and a pile with multiple defects systematically using the total probability theory. A pile capacity reduction factor is presented to account for the effect of the considered pile defects on the pile capacity. Formulae for calculating the coefficient of variation of the pile with defects are formulated. The reliability analysis is carried out in the framework of load and resistance factor design. An example is investigated to illustrate the proposed method. The results indicate that the impact of the possibility of multiple defects presence on the reliability of piles can be quantitatively evaluated using the proposed method in a rational way. The reliability of a pile is adversely affected by the presence of pile defects. The reliability of the pile will be overestimated if the possibility of multiple pile defects presence is not taken into account. If the correlation between two types of defects is not considered, the reliability of the pile will also be overestimated.

1 INTRODUCTION

Large-diameter bored piles are commonly used to support heavy structures such as high-rise buildings and bridges. From time to time, however, due to some factors that can influence the quality of piling on a particular site, such as the variability of ground conditions across the site and with depth, knowledge of the specific ground conditions gained from a detailed site investigation, contractor skill and experience with a given pile type under similar operating conditions, supply of materials of correct quality, appropriateness of construction procedures for the particular soil and groundwater conditions, and other factors (Cameron and Chapman 2004), minor or major defects may be introduced during or after pile construction. Some examples of defects are voids, soil inclusions, honeycombing, cracks, necking, and rebar corrosion (Fleming et al. 1992). To ensure the safety of pile foundations and to avoid the use of excessively conservative designs, some nondestructive evaluation (NDE) tests are often conducted after pile construction, such as cross-hole sonic logging (CSL), sonic echo testing, impedance logging, and impulse response testing.

Defects that are present within a pile are not detected completely by the current NDE methods and therefore some defects may remain within the pile foundation throughout its service life (Finno and Gassman 1998; Iskander et al. 2003). Several experimental studies (Baker et al. 1993; Hassan and O'Neill 1998; Chernauskas and Paikowsky 1999; Iskander et al. 2003) have addressed the ability of CSL to detect defects in piles. Based on these studies and from expert opinion, there is a lower limit on the size of defects that can be detected by CSL. Baker et al. (1993) found that CSL could only detect defects that occupied about 15% of the cross-sectional areas of the drilled shafts. O'Neil and Sarhan (2004) found that rebar corrosion is typically undetectable with conventional NDE tests and its effect is becomes severe many years after the installation of a drilled shaft. These defects can lead to unsatisfactory performance of pile foundations, particularly when a pile is subject to bending, or delays in construction (O'Neil et al. 2003; Sarhan et al. 2002, 2004; Poulos 2005), which may further impact the reliability of pile foundations. Therefore, it is necessary to investigate the reliability of pile foundations considering the possibility of defects presence. Zhang et al. (2006) studied the reliability of single bored piles with toe debris. However, the reliability of bored piles with multiple defects is not sufficiently investigated.

The objective of this paper is to propose a methodology to quantitatively evaluate the reliability of pile foundations considering the possibility of multiple pile defects presence. For illustrative purposes, this paper will focus on voids and rebar corrosion. Discussions on other defects, such as cracks, soil inclusions, and toe debris are beyond the scope of the paper. The probability of failure of the pile is formulated with a consideration of the possibility of multiple defects presence. A pile capacity reduction factor is presented to take into account the effect of pile defects on the pile capacity. Formulae for calculating the coefficient of variation of the pile capacity with defects are formulated. An example is presented to illustrate the proposed method.

2 RELIABILITY OF PILES WITH MULTIPLE DEFECTS

Consider the case of single bored piles with two types of defects, namely voids and rebar corrosion, along with other types of imperfections such as cracks, necking, and toe debris. The pile performance is still uncertain even when the pile is free from the considered two types of defects due to the presence of other types of imperfections as well as many other sources of uncertainty such as spatial variability of soils, various construction effects, and load effects. Since the effects of the defects could be correlated, the probability of failure of the pile due to the concurrent presence of those types of defects may not be the sum of the probability of failure due to individual types of defects. Based on the total probability theorem (e.g., Ang and Tang 2006), the probability of unsatisfactory performance of the pile with two types of defects, p_f, can be calculated as follows:

$$p_f = P(F\,|\,\overline{E})(1-p_1-p_2-p_{12}) + P(F\,|\,E_1)p_1 + P(F\,|\,E_2)p_2 + P(F\,|\,E_{12})p_{12} \qquad (1)$$

where p_1, p_2 and p_{12} = occurrence probabilities of the first type of defect alone, the second type of defect alone, and the concurrent occurrence of both types of defects, respectively; F = event of pile failure; E_1, E_2, E_{12} and $\bar{E}$ = events of the first type of defect alone, the second type of defect alone, the concurrent presence of both types of defects, and the first or the second type of defect absence, respectively; $P(F|\bar{E})$ and $P(F|E_i$, i = 1, 2, 12) = conditional probabilities of unsatisfactory performance of the pile given the absence and presence of defects, respectively.

The evaluation of conditional probabilities $P(F|\bar{E})$ and $P(F|E_i$, i = 1, 2, 12) can be formulated as follows. The probability of failure, p_f, can be expressed in terms of β as follows:

$$p_f = 1 - \Phi(\beta) \qquad (2)$$

Where Φ = standard normal distribution function; β = reliability index. It can be seen that the probability of failure can be calculated based on the calculated β The reliability index of a pile can be calculated using the first-order reliability method. If both resistance and load effects are lognormal variates, then the reliability index for a linear performance function can be written as (Withiam et al. 2001)

$$\beta = \frac{\ln\left(\left[\dfrac{\lambda_R FS(\dfrac{Q_D}{Q_L}+1)}{(\lambda_{QD}\dfrac{Q_D}{Q_L}+\lambda_{QL})}\right]\sqrt{\dfrac{1+COV_{QD}^2+COV_{QL}^2}{1+COV_R^2}}\right)}{\sqrt{\ln((1+COV_R^2)(1+COV_{QD}^2+COV_{QL}^2))}} \qquad (3)$$

where FS = factor of safety in the traditional allowable stress design; λ_R and COV_R = bias factor and coefficient of variation (COV) of the pile capacity, respectively; Q_D and Q_L = nominal values of dead load and live load, respectively; λ_{QD} and λ_{QL} = bias factors for the dead load and live load, respectively; COV_{QD} and COV_{QL} = coefficients of variation for the dead load and live load, respectively; γ_D and γ_L = load factors for the dead load and live load, respectively.

As can be seen from Eq. (3), only two parameters, λ_R and COV_R, are associated with the pile capacity. All other parameters are associated with the loads. If a pile contains voids or rebar corrosion, the pile capacity will be adversely affected. In other words, the statistics associated with the pile capacity will be altered. For instance, λ_R will be reduced while COV_R may be increased. For simplicity, COV_R for a pile with voids or rebar corrosion is assumed to be the same as that for a pile free of voids or rebar corrosion. Under this assumption, only λ_R for a pile with voids or rebar corrosion needs to be determined to calculate the corresponding reliability index using Eq. (3).

To provide a measure of the effect of voids or rebar corrosion, following Poulos (1997) and O'Neill and Sarhan (2004), a pile capacity reduction factor, R_F, is used,

$$R_F = \frac{Q_d}{Q_0} \tag{4}$$

in which Q_0 = failure load of a pile without defects and Q_d = failure load of a pile with defects. Strictly speaking, R_F should be treated as a random variable. Due to lack of sufficient statistical data for R_F, R_F is treated as a deterministic quantity in this study, but its value will depend on the type of defect, the defect size, and the pile specifics. Once R_F is obtained, the bias factor of the capacity of the pile with defects, λ_{RD}, is given by

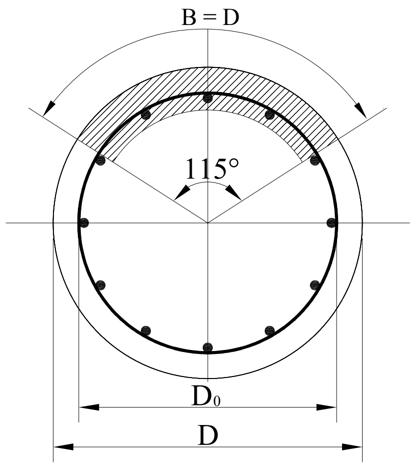
$$\lambda_{RD} = R_F \lambda_R \tag{5}$$

Thus, the reliability of the defective pile can also be calculated using Eq. (3) by replacing λ_R with λ_{RD}. Then, the conditional probability of unsatisfactory performance can also be calculated using Eqs. (2) and (3).

3 IMPACT OF DEFECTS ON PILE CAPACITY

The presence of defects does not always impair the ability of pile shaft to carry its intended load. If defects occur within a zone of high structural stress within a pile shaft, however, the capacity of the pile will be adversely affected and the structural capacity will need to be reduced for design purposes. Following Sarhan et al. (2004), such zones are termed critical zone in this paper. For the case of bored piles to resist axial load, the current design practice is to assume that the stress remains constant along the entire pile shaft. This practice neglects any load transfer through soil-shaft contact, thus resulting in the critical zone for axial stress being the entire length of the shaft. However, the critical zone is the top 12.1D for flexural or combined loading (Sarhan et al. 2004), where D is pile diameter.

For the purpose of illustration, the defects, such as voids and rebar corrosion, are considered to investigate the impact of defects on pile capacity. In the following sections, the void along, the rebar corrosion alone, and the concurrent presence of both types of defects are referred as cases 1, 2, and 3, respectively. The considered void occupies 15% of the cross-sectional areas of the pile shaft. The length of the void is not a variable and is equal to the pile diameter. The void is entirely located within the concrete cover (arch length = pile diameter). Fig. 1 shows the parameters that define the geometry of the void defect (Sarhan et al. 2004). The rebar corrosion is simulated by replacing the noncorroded rebar with a smaller diameter rebar, which results in the simulated corroded rebar having a reduced cross sectional area of that of the noncorroded rebar. The considered rebar corrosion denotes corrosion of reinforcing encased within the concrete, which results in 22% reduction in total steel area. Note that when corrosion of rebar occurs within a void, namely case 3, the considered rebar corrosion results in 2.5% reduction in total steel area. The steel percentage refers to the percentage of total steel lost from all reinforcing bars in case 2 and only from three reinforcing bars in the void in case 3. Based on studies (Sarhan et al. 2004), for a considered 1.0m diameter bored pile, the pile capacity reduction factors are 0.89, 0.94, and 0.85 for cases 1, 2, and 3, respectively. It can be seen that the concurrent presence of the void and rebar corrosion has the most adverse impact on the pile capacity. The rebar corrosion has a slight impact on the pile capacity.



B = Arch length.
D = Pile diameter.
D_0 = Diameter of reinforcement cage.

Fig.1 Parameters of void (after Sarhan et al. 2004)

4 EXAMPLE

The reliability of bored piles considering the possibility of void or rebar corrosion presence is illustrated in this worked example. A similar methodology can be applied to study the reliability of bored piles with more than two types of defects.

The following load statistics are adopted: λ_{QD} =1.08, λ_{QL} =1.15, γ_D =1.25, γ_L =1.75, COV_{QD} =0.13, COV_{QL} =0.18 and Q_D/Q_L =2.0. These statistics were used in developing the LRFD bridge design specifications (Withiam et al. 2001). A FS = 2.5 is adopted for the analysis herein. McVay et al. (1998) calibrated the design and construction procedures outlined by McVay et al (1992) for bored piles founded on rock. When the soil shaft resistance, the rock shaft resistance, and the end bearing are all considered, the bias factor and COV of the pile capacity are λ_R = 1.15 and COV_R = 0.17. The test piles in the calibration exercise are assumed to have been constructed properly. If a void or a rebar corrosion exists, then λ_R will decrease due to the reduction in the pile capacity.

Based on the data acquisition (O'Neill and Sarhan 2004), the occurrence probability of the considered void is 0.40 for the case of pure axial loading, which consists of 0.16 for the void along presence and 0.24 for the concurrent presence of the void and the rebar corrosion. Since the data for occurrence probability of rebar corrosion are not available at this time, following O'Neill and Sarhan (2004), it is assumed that the occurrence probability of the rebar corrosion is 0.05 for the case of pure axial loading. The most likely position for the rebar corrosion will be close to the ground surface so that it is always located within the critical zone.

After obtaining the reduction factor, the resulting bias factor $_{RD}$ for a pile with void or rebar corrosion can be calculated using Eq. (5), which are 1.02, 1.08, and 0.89 for cases 1, 2, and 3, respectively. Accordingly, the reliability index and the corresponding probability of failure of the defective pile can be calculated using Eqs. (3) and (2), respectively, which are 3.07, 3.27, and 2.91 for cases 1, 2, and 3, respectively. The corresponding probabilities of failure are 1.05×10^{-3}, 5.33×10^{-4}, and 1.82×10^{-3} for cases 1, 2, and 3, respectively. The reliability index for an intact pile without voids or rebar corrosion, 3.50, and the corresponding probability of failure, $P(F|\bar{E})$ = 2.33×10^{-4}, account for other types of imperfections besides voids and rebar corrosion as well as many other sources of uncertainty. The reliability index of the pile with the void and rebar corrosion, 2.91, is significantly smaller than 3.50 for the intact pile without voids or rebar corrosion, which indicates that the performance of the pile is adversely affected due to the concurrent presence of void and rebar corrosion.

Having determined the occurrence probabilities of defects and the conditional probabilities of unsatisfactory performance of the pile given the absence and presence of defects, the probability of unsatisfactory performance of the pile can be calculated using Eq. (1). The corresponding probability of failure of the pile is 7.60×10^{-4}, which is higher than 2.33×10^{-4} for the intact pile without voids or rebar corrosion. This indicates that when the possibility of multiple pile defects presence is not taken into account, the reliability of the pile is overestimated. In addition, if the effect of concurrent occurrence of void and rebar corrosion is not taken into account, namely $p_{12} = 0$ in Eq. (1), the probability of failure becomes 3.23×10^{-4}. Compared with the case that the correlation between void and rebar corrosion is considered, the reliability of the pile is overestimated.

5 CONCLUSIONS

This paper has developed a methodology to evaluate the reliability of bored piles with a consideration of possibility of multiple defects presence. Results from the example indicate that the impact of the possibility of multiple defects presence on the reliability of piles can be quantitatively evaluated using the proposed method in a rational way. The reliability of the pile is adversely affected due to the concurrent presence of void and rebar corrosion in the example. For instance, the reliability index of the pile with the void and rebar corrosion, 2.91, is significantly smaller than 3.50 for the intact pile without voids or rebar corrosion. If the possibility of multiple pile defects presence is not taken into account, the reliability of the pile will be overestimated. In addition, if the correlation between void and rebar corrosion is not considered, the reliability of the pile will also be overestimated.

ACKNOWLEDGMENT

This research was substantially supported by National Key Project of Scientific and Technical Supporting Programs Funded by Ministry of Science and Technology of China (Project NO. 2006BAB04A05).

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