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NOMINAL CAPACITY OF BORED PHC NODULAR PILES BASED ON LOADING TEST DATA CONSIDERING LOGNORMAL DISTRIBUTION

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1. Introduction

The correlation formulations for vertical capacity of piles based on the loading test data are often based on the analysis assuming normal distribution of data (e. g. Horiguchi & Karkee, 1995). Recent investigation on a database of 51 loading tests on fully instrumented bored PHC nodular piles, covering different ground conditions throughout Japan, indicate that lognormal distribution is better suited for such analysis. The database consists of slow maintained tests with the incremental loads maintained for 30 minutes, and the loading cycled back to zero incrementally. The pile top applied load P_0, top movement S_0 and toe movement S_P were measured directly. Axial distribution of P_0 was obtained by strain gage measurements. Load P_0 was increased until S_0 reached at least 10% of pile nodule diameter (D), except when creep deformations were excessive to make maintaining the load difficult.

The measured resistance (R_m) from loading tests was defined as P_0 at S_0=0.1D following the Japanese Geotechnical Society standard. In few cases where maximum S_0 could not reach 0.1D, R_m was estimated by extrapolation based on the hyperbolic curve fitted to the measured data. The details are given in Karkee *et al.* (1998). The unit shaft resistance in different gage intervals was obtained from axial distribution of R_m.

Standard penetration test N-values and classification of soil type constitute the basic information available for foundation design in practice, particularly in small to medium size construction projects where the PHC nodular piles are mostly used. Accordingly, correlation formulations for the vertical resistance are given in terms of N-values and simple soil type classification.

2. Correlation Equations

As the cement grout in bored PHC nodular piles is designed to have fairly high strength (Karkee *et al.* 1998, Horiguchi & Karkee 1995), the unit shaft resistance τ was computed based on the drilled hole diameter D_b. The unit toe resistance q was based on the nodule diameter D. Soil types within different strain gage intervals were broadly classified as sand, clay or humus, depending on the major content. The average N-value and the unit shaft resistance in the different intervals are designated as N_s, N_c or N_h and τ_s, τ_c or τ_h respectively, depending on whether the soil type is classified as sand, clay or humus. The N-value N_P of the pile toe was obtained as the average in the region between 1.0D above and 1.0D below the nodule near the lower end of pile. The soil in the pile toe region was mostly sandy type.

Four correlation equations for the nominal values of q, τ_s, τ_c and τ_h, in terms of N_P, N_s, N_c, and N_h respectively are developed based on the following assumptions:

(*a*) Straight line relationship of the form $y=a+bx$.
(*b*) Distribution of the data follows log-normal distribution given by Equations 1, where λ is the mean of $\ln Y$ and ζ is standard deviation of $\ln Y$, Y being either q, τ_s, τ_c or τ_h, depending on the case under consideration. In terms of the mean μ and the standard deviation σ of Y, the values of ζ and λ are given by Equations 2 and 3 respectively.

$$f_Y(Y)=\frac{1}{\sqrt{2\pi}\,\zeta Y}\exp\left[-\frac{1}{2}\left(\frac{\ln Y-\lambda}{\zeta}\right)^2\right],\ 0\le Y<\infty \qquad (1)$$

$$\zeta=\sqrt{\ln\left(1+\frac{\sigma^2}{\mu^2}\right)} \qquad (2)$$

$$\lambda=\ln\mu-\frac{1}{2}\zeta^2 \qquad (3)$$

(*c*) The nominal values of q, τ_s, τ_c, and τ_h, designated as q_n, τ_{sn}, τ_{cn}, and τ_{hn} respectively, are defined as values that have at least 70% confidence of not exceeding the measured value.
(*d*) The equations for q_n, τ_{sn}, τ_{cn}, and τ_{hn} are applicable for certain maximum values of N_s, N_c, N_h and N_P respectively, such that the mean to nominal ratio k_R is at least 1.1 as recommended by Becker (1996).

Under these assumptions, the correlation equations for the respective nominal resistances q_n, τ_{sn}, τ_{cn}, and τ_{hn} are given by Equations 4 to 7 (Karkee *et al.* 1998).

$$q_n=155\times N_P\quad (kPa),\ N_P\le 30 \qquad (4)$$

$$\tau_{sn}=24.0+6.0\times N_s\quad (kPa),\ N_s\le 30 \qquad (5)$$

$$\tau_{cn}=24.0+5.3\times N_c\quad (kPa),\ N_c\le 15 \qquad (6)$$

$$\tau_{hn}=5.0+5.2\times N_h\quad (kPa),\ N_h\le 8 \qquad (7)$$

3. Measured and Computed Nominal Resistance

Nominal resistance R_n of a bored PHC nodular pile of given length at a site can be obtained from Equations 4 to 7. If the length of pile shaft in meters in contact with sand, clay and humus are L_s, L_c and L_h respectively, the nominal resistance R_n in kN is given by Equation 8,

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where D and D_b are in meters. Nominal resistance R_n for all the test piles was computed from Equation 8 based simply on the soil profile information. Then R_n and R_m were compared by defining the ratio $\Psi_{mn}=R_m/R_n$. Distribution of Ψ_{mn} is shown in Figure 1, where the probability density (PD) based on the lognormal distribution represents the data very well.

$$R_n = \frac{\pi D^2 q_n}{4} + \pi D_b \sum \left\{ \tau_{sn} L_s + \tau_{cn} L_c + \tau_{hn} L_h \right\} (kN) \quad (8)$$

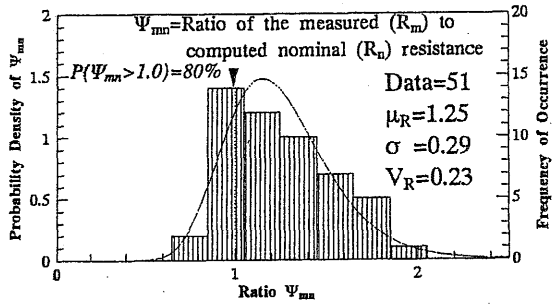

Figure 1: Ratio of measured to nominal resistance Ψ_{mn}.

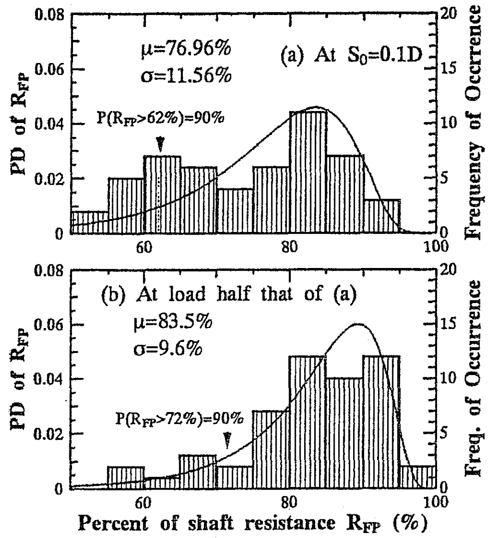

Figure 2: Share of Load Taken by Shaft Resistance

4. Portion of Load Taken by Shaft Resistance

Figure 2(a) shows the share of P_0 at S_0=0.1D taken by shaft resistance, where a tendency of two groups can be noted and the PD based on lognormal distribution does not seem to represent the data adequately. However, when the load is halved (factor of safety=2), the share of shaft resistance follows well the lognormal distribution in Figure 2(b). The 90% confidence limit for the share of shaft resistance is about 72%.

5. Factor of Safety (FS) and Pile Head Movement

Another important aspect in pile capacity is the extent of movement under loading conditions expected in practice. Distribution of pile head movement at different FS levels obtained directly from the measured load movement curves are given in Figure 3.

Figure 3 depicts the extent of movement to be expected at different service load conditions. Again, the lognormal distribution is seen to closely represent the data. The 95% confidence limit, meaning 95% confidence of the movement not exceeding the limit, is 13mm, 9mm and 7mm for FS of 2.0, 2.5 and 3.0 respectively. It can also be noted that the decrease in the expected movement is not in proportion to the increase in the FS.

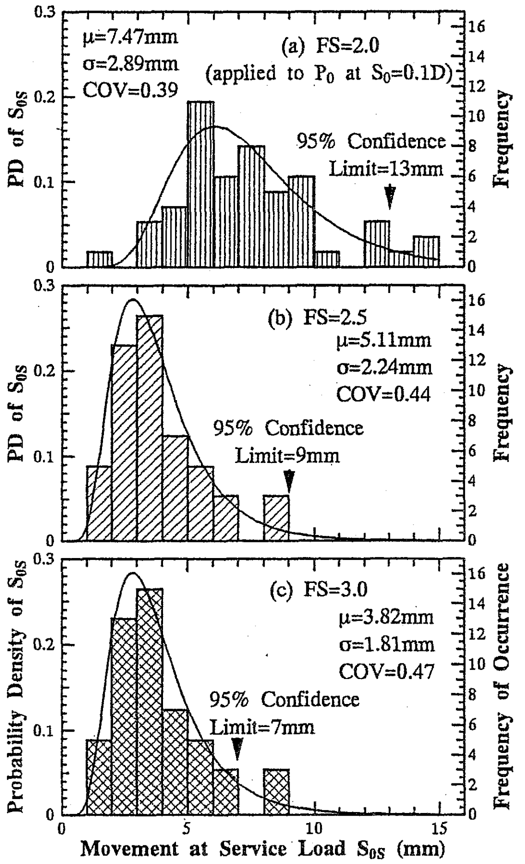

Figure 3: Movement and Service Load Conditions

6. Conclusions

Lognormal distribution is found to represent closely the shape of data distribution in all the cases in the analysis. Extent of pile head movement decreases and lies within a closer range as the service load decreases, and the 95% confidence limit for movement is 13mm, 9mm and 7mm respectively for FS of 2.0, 2.5 and 3.0.

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対数正規分布を考慮した載荷試験結果による埋め込みPHC節杭の公称支持力

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