ESTIMATION OF RELATIONS BETWEEN POINT BEARING LOADS AND SETTLEMENTS OF BORED PRECAST PILES USING SOIL BORING LOG INFORMATIONS

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ABSTRACT

A new estimation method is proposed for the relationship of the point bearing loads and point settlements of bored precast piles installed in sandy supporting strata by preboring or inner excavation. The method is derived using analyses by finite element method, back-analyses by neural network and regression analyses. The piles have widened holes at the pile points which are filled with cement milk. Nomographs are prepared and, if the diameter of the widened part, embedded length of the part into the supporting stratum, N-value and effective overburden pressure on the surface of the stratum are given, we can estimate the relations by manual calculation.

Key words: bearing capacity, finite element method, load test, penetration test, pile, statistical analysis, vertical load (IGC: H1/E4/E13)

INTRODUCTION

The point bearing capacity of bored precast piles can be estimated most reliably by loading tests. But because of the cost and time necessary for loading tests, the point bearing capacity is often estimated by SPT N-values in Japan. Estimation methods for bored precast piles using N-values were studied by Okahara (1990) and Yamagata et al. (1992). Using loading test results, where axial strains were measured near pile points, axial forces were calculated and divided by sectional areas $\pi d^2/4$, where $d$ is the outside diameter of a pile, and point bearing capacities were evaluated. Collecting point bearing capacities and N-values in pairs, relations between them were analysed by simple regression.

The bored precast piles in the present study were installed by preboring or by inner excavation. In installation by preboring, a hole is bored by, for example, an earth auger. Then cement milk is poured into the lower part of the bore hole and the pile is inserted and pushed down into the cement milk. In installation by inner excavation, inserting an auger into the inside of a hollow pile whose point is open and drilling the ground below the pile point, the pile is set into the ground by loading a small weight or by driving slightly on its head. After this drilling reaches the supporting stratum, a hole is drilled below the pile point and cement milk is poured into it from the bottom of the auger. The pile is pushed down into the cement milk. In these two installations, the bore holes are usually widened or enlarged in the supporting strata. After hardening of the cement milk, axial forces of the piles can be transmitted to the supporting strata. The widened part filled with the hardened cement milk is named the “widened part” for simplicity.

In the present study, a new estimation method is proposed for the relationship between point bearing load and point settlement of the bored precast piles, where supporting strata are sandy. The point bearing load and the point settlement are defined as the axial force and settlement of the pile at the surface of the supporting stratum, as shown in Fig. 1(a). Inputs used in the estimation method are $D$, $H$, $N$ and $\sigma'_s$, where, as shown in Fig. 1(b), $D$ = a diameter of the widened part, $H$ = the embedded depth of a widened part into a supporting stratum, $N$ = SPT N-value and $\sigma'_s$ = effective overburden pressure acting on the surface of the supporting stratum.

Using the data from a number of loading tests, it may be possible to do multiple regression analyses, where independent variables are $D$, $H$, $N$ and $\sigma'_s$ and dependent variables are point bearing loads. But with independent variables being four in number, the amount of data necessary for the analyses increases to the fourth power. In the present study, since there are not enough loading test results to allow multiple regression analyses, the finite element method and neural networks are used and simple regression analyses are carried out.

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Manuscript was received for review on August 21, 1996.

Written discussions on this paper should be submitted before January 1, 1999 to the Japanese Geotechnical Society, Sugayama Bldg. 4F, Kanda Awaji-cho 2-23, Chiyoda-ku, Tokyo 101-0063, Japan. Upon request the closing date may be extended one month.
point bearing loads $P_1$, $P_2$, $P_3$, $P_4$, $P_5$, and $P_6$ which correspond to point settlements 0.01$D$, 0.02$D$, 0.04$D$, 0.06$D$ and 0.08$D$ respectively. Thus two groups of sets of $D$, $H$, $\sigma'_c$, soil parameters, $P_1$, $P_2$, $P_3$, $P_4$, and $P_5$ are generated. One group is data for neural networks’ learning and the other for verification. Details are given below in FINITE ELEMENT ANALYSES.

STEP 2: Constructing a neural network whose inputs are $D$, $H$, $\sigma'_c$, $P_1$, $P_2$, $P_3$, $P_4$, and $P_5$ and outputs are soil parameters, we make the neural network learn using the data for learning generated in STEP 1. The network is named Neural Network 1. After learning, the accuracy of outputs by Neural Network 1 is examined using the data for verification generated in STEP 1. Then we can calculate soil parameters of a supporting stratum by Neural Network 1 if $D$, $H$, $\sigma'_c$, $P_1$, $P_2$, $P_3$, $P_4$, and $P_5$ are given. Details are explained below in CONSTRUCTION OF NEURAL NETWORK 1.

STEP 3: A number of loading test results are collected where maximum point settlements are larger than 10% of diameters of piles, i.e., 0.1$D$. If supporting strata are diluvial sandy soil, point bearing loads usually increase monotonously as point settlements increase, even though point settlements are fairly large, for example 0.1$D$ or more. Hence point bearing loads at point settlement equal to 0.1$D$ are often used in Japan instead of ultimate point bearing loads. As 0.1$D$ is nearly equal to 0.08$D$, 0.08$D$ is set as the maximum point settlement in STEP 2. When we have loading test results, soil boring logs and reports on pile construction which describe details of the widened parts, $D$, $H$, $\sigma'_c$, $P_1$, $P_2$, $P_3$, $P_4$, and $P_5$ are evaluated. They are input to Neural Network 1 and the soil parameters of supporting strata are calculated. Details are below in ESTIMATION OF SOIL PARAMETERS OF LOADING TESTS.

STEP 4: Using the soil boring logs, we evaluate $N$’s of the supporting strata and so we have sets of soil parameters and normalized $N$-value $N/\sqrt{\sigma'_c}$. Simple regression analyses are carried out and regression straight lines of soil parameters $\sim N/\sqrt{\sigma'_c}$ are derived. Details are explained in REGRESSION ANALYSES.

STEP 5: Another neural network is constructed whose inputs are $D$, $H$, $\sigma'_c$ and soil parameters and outputs are $P_1$, $P_2$, $P_3$, $P_4$, and $P_5$. Using again the data for learning generated in STEP 1, we make the network learn. The network is named Neural Network 2. After learning, the accuracy of outputs by Neural Network 2 is examined using the data for verification generated in STEP 1. Then with Neural Network 2, we can calculate $P_1$, $P_2$, $P_3$, $P_4$, and $P_5$ when $D$, $H$, $\sigma'_c$ and soil parameters of a supporting stratum are given. The network is equivalent to FEM in calculation of the outputs. Details are explained in CONSTRUCTION OF NEURAL NETWORK 2.

STEP 6: The regression lines and Neural Network 2 are combined into nomographs and we can calculate $P_1$, $P_2$, $P_3$, $P_4$, and $P_5$ by manual calculation when $D$, $H$, $\sigma'_c$ and $N$ are given. Details are explained in the chapter of ESTIMATION METHOD.

![Fig. 1. Definition of point bearing loads: (a) A bored precast pile, (b) Point bearing load](image)

![Fig. 2. Derivation procedure of estimation method](image)
FINITE ELEMENT ANALYSES

It is assumed that the behavior of the pile shown in Fig. 1(a) can be approximated by that of the pile shown in Fig. 1(b) where the ground above the supporting stratum is removed and effective overburden pressure $\sigma'_i$ acts on the surface of the stratum. Using the finite element model explained in this chapter, preliminary analyses are carried out and we conclude the following: if friction does not act on the pile above the supporting stratum, that is to say, the shaft of the pile above the supporting stratum is frictionless, the stiffness and strength of the ground above the supporting stratum will have little influence on the point bearing loads. In the loading tests collected in ESTIMATION OF SOIL PARAMETERS OF LOADING TESTS, almost all of the shafts of piles above the supporting strata were coated in order to reduce friction by, e.g., bitumen compound. Hence it can be said that the assumption is valid.

An example of an axi-symmetric finite element model representing a widened part, a pile and a supporting stratum is shown in Fig. 3. The widened part and the pile are considered as a single solid body whose upper surface is on a level with that of the supporting stratum. Young's modulus is $2.1 \times 10^7$ kPa and Poisson's ratio is 0.167. A uniformly distributed load acts on the upper surface of the solid body, whose resultant load is equal to a point bearing load.

Constitutive equations proposed by Duncan et al. (1980) are used for supporting strata. Applicability of the constitutive equations to problems on point bearing loads of piles embedded into sandy strata were examined by the authors and the equations were confirmed to represent the loading test results with good accuracy (Yamazaki et al., 1995). Tangent Young's modulus $Et$ and tangent compressive bulk modulus $B$ of soil are expressed by the following equations.

$$ Et = \frac{1 - R_c (1 - \sin \phi) (\sigma'_i - \sigma'_j)^2}{2c \cos \phi + 2\sigma'_i \sin \phi} \frac{K - P_s}{\sigma'_i} \cdot \left( \frac{\sigma'_i}{P_s} \right)^m $$

$$ B = K_s \cdot \frac{\sigma'_i}{P_s} \cdot \left( \frac{\sigma'_i}{P_s} \right)^n $$

where $\phi$ and $c$ are angle of internal friction and cohesion, $\sigma'_i$ and $\sigma'_j$ are maximum and minimum effective principal stresses, $P_s$ is atmospheric pressure, $K$ is initial tangent Young's modulus non-dimensionalized with respect to $P_n$, $K_s$ is tangent compressive bulk modulus non-dimensionalized with respect to $P_n$. $R_c$ and $R_t$ is correction coefficient for shearing strength. The exponents $m$ and $n$ express the influence of $\sigma'_i$ on $B$ and $Et$.

The following conditions are imposed on the soil parameters. Since the supporting strata are sandy in the present study, $c$ is set equal to zero. Since $K_s=0.25$ $K=1.25$, $R_c=0.57-0.90$, $m=0.0-0.52$, $n=0.21-0.78$ in sandy soil (Duncan et al., 1980), it is assumed that $K_s=0.75K$, $R_c=0.9$, $m=0.3$, $n=0.5$. Soil parameters to be determined by loading test results are reduced to $\phi$ and $K$. The reason why soil parameters are reduced to $\phi$ and $K$ are as follows:

1. As described later, soil parameters are evaluated using $N$ and $\sigma'_i$. Since parameters $R_c$, $m$ and $n$ seem to have little relation to $N$, parameters $\phi$, $K$ and $K_s$ are kept.

2. In the next chapter, a neural network is constructed whose inputs are $D$, $H$, $\sigma'_i$, $P_s$, $P_n$, $P_s$ and $P_n$, and outputs are the soil parameters. We examined preliminarily whether all of $\phi$, $K$ and $K_s$ can be determined uniquely by the inputs and it was found that only a pair of $\phi$ and $K$ or a pair of $\phi$ and $K_s$ could be determined uniquely. Since $K$ is a more fundamental parameter than $K_s$, the pair of $\phi$ and $K$ was selected.

The coefficient of earth pressure at rest $K_0$ is set equal to 1.0 for the following reason. Because sandy supporting strata in Japan generally belong to diluvial deposits, it is assumed that $K_0$ is greater than 1.0. Kishida et al. (1985) examined the effect of $K_0$ on the point bearing load of a pile and found that if $K_0$ increases to 1.0, the bearing load increases, and if $K_0$ is greater than 1.0, the bearing load remains almost constant. As $K_0$ is assumed to be greater than 1.0 but a $K_0$ greater than 1.0 has little influence on the increase of the bearing load, $K_0$ is set equal to 1.0.

Nonlinear calculation is carried out incrementally. Estimating the load at settlement 0.082 by trial calculation by FEM, the load increment is set equal to 1/90 of the load. The load is increased by load increment stepwise. It is assumed that the relation between stress and strain increments are assumed to be linear during the load increment and tangent stiffness is estimated based on the stress state before the load increment is applied.
In order to generate data for the neural networks’ learning and verification as shown in STEP 1 of Fig. 2, the following calculations are carried out. First, fifty-two sets of $\phi$, $K$, $D$, $H$ and $\sigma'_r$ are generated for learning and shown in Table 1. The range of numerical values of $D$, $H$ and $\sigma'_r$ are set so that they can cover the range of $D$, $H$ and $\sigma'_r$ of the loading tests of Table 3. The values of $\phi$ and $K$ are probable values for dense sandy soil (Duncan et al., 1980). Using these values as input, $P_1$, $P_2$, $P_3$, $P_4$, $P_5$ and $P_6$ are calculated by FEM. Then fifty-two sets of $D$, $H$, $\sigma'_r$, $K$, $P_1$, $P_2$, $P_4$, $P_5$ and $P_6$ are generated and prepared for the neural networks’ learning. Another twenty-eight sets of $\phi$, $K$, $D$, $H$ and $\sigma'_r$ are generated for verification and shown in Table 2. In the first eleven sets (No. 1–11), ranges of $D$ and $H$ are the same as those of Table 1 but the sets of $D$, $H$, $\sigma'_r$, $\phi$ and $K$ are different from those in Table 1. In the latter sets (No. 12–28), $D$, $H$, $\sigma'_r$ are the same as those of loading tests of Table 3. The values $\phi$ and $K$ are set by regression lines, using $N$ and $\sigma'_r$ of the loading tests. The loading tests and the regression lines will be explained later. $P_1$, $P_2$, $P_3$, $P_4$ and $P_5$ are calculated by FEM. Then twenty-eight sets of $\phi$, $K$, $D$, $H$, $\sigma'_r$, $P_1$, $P_2$, $P_4$, $P_5$, $P_6$ and $P_8$ are generated for verification. Since the data necessary for verification may be less in number than that for learning, the full twenty-eight sets are generated.

An example of the relationship between point bearing load and point settlement is shown in Fig. 4, where the loads $P_1$, $P_2$, $P_4$, $P_5$ and $P_8$ and the corresponding settlements are indicated by $\bigcirc$. The point bearing loads consist of loads supported by the end of the widened part and loads supported by friction acting on the side of the widened part, and the two components are shown in the

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Unit: $D$, $H$ (m), $\sigma_r$ (kPa), $\phi$ (°), $K$ (no dimension).

![Fig. 4. An example of load-settlement relation calculated by FEM](image-url)
Table 3. Loading tests for regression analyses

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Unit: $D$, $H$ (m), $\sigma'_i$ (kPa), $P_1$–$P_8$ (MN), PB: Preboring, IE: Inner excavation.

same figure. The latter loads are bigger than the former when the point bearing loads are small, and the former loads are much bigger when the point bearing loads are big.

CONSTRUCTION OF NEURAL NETWORK 1

A Neural Network

A neural network simulates behavior characteristic of a biological neuron network (e.g. Baba et al., 1994; Anderson, 1995). There are two kinds of networks: a multi-layered neural network and a fully connected neural network. The multi-layered network is used in the present study, as shown in Fig. 5. The network consists of an input layer, hidden layers and an output layer. Equations representing the behavior of a neuron which belongs to the $s$-th layer are

$$x_j = f\left(\sum_{i} w_{ij} x_i - \theta_j\right)$$

(3)

$$f(x) = \frac{1}{1 + \exp (-x)}$$

(4)

where $x_i$ is the output of neuron $j$, $w_{ij}$ is the connection weight between neuron $j$ belonging to the $s$-th layer and neuron $i$ belonging to the $(s-1)$th layer, $n$ is the number of neurons in the $s$-th layer, and $\theta_j$ is the threshold value of neuron $j$, as shown in Fig. 5(b).

Learning is carried out by back-propagation algorithms which are fundamental for learning in multilayered neural networks. After learning, the numerical values of the connection weights and the thresholds of all neurons are determined and the network can calculate the outputs when the inputs are evaluated and input to the network.

Learning of Neural Network 1

A neural network named Neural Network 1 is constructed whose inputs are $D$, $H$, $\sigma'_i$, $P_1$, $P_2$, $P_4$, and outputs are $\phi$ and $K$, as shown in Fig. 6(a). The network consists of three layers, i.e., an input layer which has eight neurons, a hidden layer which has six and an output layer which has two. The reason why the number of neurons in the hidden layer is six is as follows. It is found by numerical experiments that total errors in case of the six neurons are smaller than those of five neurons and nearly equal to those of seven neurons. The network learns, using the data from fifty-two sets of numerical values of $\phi$, $K$, $D$, $H$, $\sigma'_i$, $P_1$, $P_2$, $P_4$, and $P_8$, which were generated in the previous chapter. Learning is finished when learning is iterated five thousand times. After learning, the network can evaluate outputs $\phi$ and $K$, when inputs $D$, $H$, $\sigma'_i$, $P_1$, $P_2$, $P_4$, $P_8$, and $P_8$ are given, that is to say, Neural Network 1 can perform back analyses.
Fig. 5. Neural network: (a) Multi-layered network, (b) Neurons $i$ and $j$

Fig. 6. Structures of Neural Networks 1 and 2: (a) Neural Network 1, (b) Neural Network 2

**Verification**

In order to clarify how precisely Neural Network 1 can yield outputs, the following verification is carried out. The twenty-eight sets of $\phi$, $K$, $D$, $H$, $\sigma'_0$, $P_1$, $P_2$, $P_3$, and $P_4$ are used which were generated for verification in the chapter FINITE ELEMENT ANALYSES. The twenty-eight sets of $D$, $H$, $\sigma'_0$, $P_1$, $P_2$, $P_3$, $P_4$, and $P_5$ are input to Neural Network 1 and twenty-eight sets of $\phi$ and $K$ are obtained as outputs. Comparisons are shown in Fig. 7 whose abscissas are the values used as inputs in the FEM and ordinates are the outputs of Neural Network 1 (NNI for short). Though the maximum error of $\phi$ is about five degrees and that of $K$ is about 300, it can be said that the network calculates outputs accurately enough, considering the precision of $N$ which will be used in the regression analyses of the later chapter. But a more accurate Neural Network 1 is desirable and the improvement will be attempted in a future study.

**ESTIMATION OF SOIL PARAMETERS OF LOADING TESTS**

Nineteen loading test results were collected. The points or positions where the strains were measured nearest to the pile points were not just on the surface of the supporting strata but also in the strata. The points or positions are called “measuring points” for simplicity. In discussions of the test results, the definition of point bearing

Fig. 7. Soil parameters used in FEM and calculated by Neural Network 1
loads and point settlements are modified as follows.

The point bearing load and the point settlement are redefined as an axial force and settlement at the measuring point, as shown in Fig. 8(a). It is assumed, as in FINITE ELEMENT ANALYSES, that the behaviors of the pile shown in Fig. 8(a) can be approximated by those of the pile shown in Fig. 8(b) where the ground above the measuring point is removed and effective overburden pressure $\sigma'_v$ acts on the surface of the supporting stratum after the removal.

The numerical values of $D$, $H$, $\sigma'_v$, $N_1$, $P_1$, $P_2$, $P_3$, and $P_4$ and the distinction between sand and sandy gravel in the tests are shown in Table 3. The $N$ is an average value in the interval between the end of a widened part and 1.0$d$ below the end. This average is adopted for the following reasons.

There are four kinds of design values of $N$ which are currently or will be used in Japan. The first three have been introduced by Yamagata et al. (1992). The first is an average value of $N$ in the interval between 4.0$d$ above and 1.0$d$ below the pile point, where $d$ is the diameter of the pile. The average is based on Meyerhof’s recommendation to use an average of soil properties in the interval (Meyerhof, 1963). The second is an average value between 1.0$d$ above and 1.0$d$ below the pile point. The third is an average value between the pile point and 1.0$d$ below the pile point. The fourth is an average value of $N_1$ and $N_2$, where $N_1$ is an average value between the pile point and 4.0$d$ above the pile point and $N_2$ is an average value between the pile point and 1.0$d$ below the pile point.

Point bearing loads consist of bearing loads at the end of the widened part and loads supported by friction acting on the side of the part. The former loads are considered more important in the present study, especially when point bearing loads are close to $P_0$. Preliminary analyses using the finite element model of the present study showed that the stiffness and strength of the ground above the end of a widened part have little influence on the bearing loads at the end of the part. From these results the third design value of $N$ is adopted. How to calculate $N$ more reasonably when supporting strata are not homogeneous will be left to a future study.

Inputting $D$, $H$, $\sigma'_v$, $P_1$, $P_2$, $P_3$, $P_4$ and $P_5$ to Neural Network 1, the network outputs numerical values of $\phi$ and $K$. From this we get nineteen sets of $\phi$, $K$, $N$ and $\sigma'_v$.

As a result of pile construction operations, $\phi$ and $K$ in the neighborhood of point bearing points may be changed and different from those of the original supporting strata and this phenomenon is not taken into account in the analyses. Since the loads $P_1$, $P_2$, $P_3$, $P_4$, and $P_5$ depend on the values of $\phi$ and $K$ in the neighborhood of the pile points as well as of the original supporting strata, $\phi$ and $K$ calculated by Neural Network 1 may be different from either of them and can be considered as equivalent parameters which take into account the effect of pile construction work.

REGRESSION ANALYSES

Since $N$-values depend on effective overburden pressure $\sigma'_v$, it is necessary to transform $N$ into a quantity which is independent of $\sigma'_v$ in order to correlate $\phi$ and $K$ with $N$. The quantity $N/\sqrt{\sigma'_v}$ proposed by Liao et al. (1986) is used. The nineteen sets of $\phi \sim N/\sqrt{\sigma'_v}$ and $K \sim N/\sqrt{\sigma'_v}$ are plotted in Fig. 9. Values in case of supporting strata of sand are dotted by $\Delta$ and those in case of supporting strata of sandy gravel by $\circ$. Since there seems no clear difference between the characteristics of the two cases and since there are not many loading test.
results for supporting strata of sandy gravel, no distinction is made between the supporting strata of sand and sandy gravel. Regression analyses yield two regression lines which are given by the following equations.

\[
\phi = 1.5 \cdot N / \sqrt{\sigma'}_v + 39.1 \quad (5)
\]

\[
K = 78 \cdot N / \sqrt{\sigma'}_v + 956 \quad (6)
\]

The coefficients of variation of the ratio (a parameter estimated by loading test; a parameter estimated by regression line) are 0.11 with respect to \(\phi\) and 0.44 with respect to \(K\) respectively.

**CONSTRUCTION OF NEURAL NETWORK 2**

**Learning of Neural Network 2**

A neural network named Neural Network 2 is constructed whose inputs are \(D, H, \sigma'_v, \phi\) and \(K\) and outputs are \(P_1, P_2, P_3, P_4\) and \(P_5\), as shown in Fig. 6(b). The neural network consists of three layers, i.e., an input layer which has five neurons, a hidden layer which has seven and an output layer which has five. The fifty-two sets of \(\phi, K, D, H, \sigma'_v, P_1, P_2, P_3, P_4, P_5\) and \(P_6\) which were generated in **FINITE ELEMENT ANALYSES** are used again and the network learns. After learning, the network can evaluate \(P_1, P_2, P_3, P_4, P_5\) and \(P_6\) when \(\phi, K, D, H\) and \(\sigma'_v\) are given, i.e., Neural Network 2 can perform the same analyses that FEM can.

**Verification**

The twenty-eight sets of \(\phi, K, D, H, \sigma'_v, P_1, P_2, P_3, P_4, P_5\) and \(P_6\) are used again which were generated for verification in **FINITE ELEMENT ANALYSES**. The twenty-eight sets of \(\phi, K, D, H\) and \(\sigma'_v\) are input to Neural Network 2 and twenty-eight sets of \(P_1, P_2, P_3, P_4, P_5\) and \(P_6\) are obtained as outputs. The values of \(P_1, P_2, P_3, P_4, P_5, P_6\) and \(P_6\) which are the outputs of the network and those of FEM are compared in order to clarify how precisely Neural Network 2 can yield outputs. Two examples of relations between point bearing load and settlement are shown in Fig. 10. The outputs of Neural Network 2 (NN2 for short), are indicated by □ and of the FEM by ◊. Case No. 5 is the example where the error or the difference between the outputs of the neural network and FEM is the greatest, and Case No. 16 where it is smallest.

It will be shown in the next chapter that the smallest ratio (loading test value : calculated value) is about 0.7 in cases of \(P_1, P_2, P_3\) and \(P_4\), where “loading test values” are values of \(P_1, P_2, P_3, P_4\) and \(P_5\) evaluated by loading tests and “calculated values” are values calculated by the method in the next chapter. The error induced by using Neural Network 2 instead of FEM may influence the value of the smallest ratio fairly significantly. Improvement of the accuracy of Neural Network 2 will be left for the future study.

**ESTIMATION METHOD**

Estimation of point bearing loads \(P_1, P_2, P_3, P_4, P_5, P_6\) is carried out as shown in Fig. 11. As inputs \(\sigma'_v, N, D\) and \(H\) are given, \(N / \sqrt{\sigma'_v}\) is calculated. From the regression line in terms of \(\phi\) or \(K\) and \(N / \sqrt{\sigma'_v}\), we can calculate \(\phi\) and \(K\). Inputting \(\phi, K, D, H\) and \(\sigma'_v\) to Neural Network 2, we can obtain \(P_1, P_2, P_3, P_4, P_5\) and \(P_6\). Values of loads calculated by this method will be called “calculated value” for simplicity.

The regression lines and Neural Network 2 are combined and the relation whose inputs are \(D, H, \sigma'_v\) and \(N\) and outputs are \(P_1, P_2, P_3, P_4, P_5, P_6\) are expressed in nomographs as shown in Fig. 12. The numeral of the abscissa is the diameter of the widened part in meters and all nine curves, i.e., three expressed by a symbol ◊, three by △ and three by ◊, belong to each diameter. For explanation, a nomograph in case of \(D = 0.8\) m is shown again in Fig. 13. The three curves expressed by ◊ correspond to the case of \(N / \sqrt{\sigma'_v}\) equal to 2.0, where the unit of \(\sigma'_v\) is kPa, the three by △ to 4.0 and the three by ◊ to 6.0. The upper, the middle and the lower curves of each symbol, i.e., ◊, △ or ◊, shown as h3, h2 and h1 correspond to the cases of \(H\) equal to 2.5D, 2.0D and 1.5D respectively. The six points on the same curve,
shown as s1, s2, s3, s4, s5 and s6, correspond to $\sigma_i$ equal to 100, 200, 300, 400, 500 and 600 kPa respectively. If a set of $D$, $H$, $N/\sqrt{\sigma_i}$ and $\sigma_i$ does not coincide with a set presented by the points of the symbol $\bigcirc$, $\triangle$ or $\diamond$, the loads are evaluated interpolatively, as explained in DESIGN VALUES OF POINT BEARING LOADS.

COMPARISON WITH LOADING TEST RESULTS

The values of $P_1$, $P_2$, $P_3$, $P_4$ and $P_5$ which are loading test values and calculated values will be compared in the following. First, the nineteen loading test results, which have been used to derive the regression line of $\phi$ or $K$ and

Fig. 13. An example of nomograph for explanation
$N/\sqrt{\sigma}$, are discussed. Then six loading test results which have not been used for the regression analyses are discussed.

Comparisons of the nineteen loading tests are shown in Fig. 14. The ordinate indicates the loading test values and the abscissa the calculated values. With respect to the ratios (loading test value: calculated value), histograms are shown in Fig. 15. Arithmetic means $\mu$, standard deviations $\sigma$ and coefficients of variation which are calculated by point estimation are also shown in the figure. Loads
which are close to ultimate bearing loads seem to be most influenced by $\phi$ and those close to initial or zero loads by $K$. Since deviation from the regression line is greater in case of $K$ than in case of $\phi$, as seen in Fig. 9, variation is the greatest for $P_t$ and the smallest for $P_s$ and $P_u$.

A comparison of the six loading tests listed in Table 4 is shown in Fig. 16. In five of the tests, maximum settlements were less than $0.08D$ and test results cannot be used in the regression analyses. One of the tests whose maximum settlement was greater than $0.08D$ was collected after the regression analyses had been carried out. The calculated values are denoted by $\Box$ and the loading test values by $\Diamond$. Similar characteristics to those of the nineteen loading tests can be seen.

### Table 4. Loading tests for verification

<table>
<thead>
<tr>
<th>No.</th>
<th>$D$ (m)</th>
<th>$H$ (m)</th>
<th>$N$</th>
<th>$\sigma';$ (kPa)</th>
<th>soil</th>
<th>installation</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.70</td>
<td>1.75</td>
<td>50</td>
<td>312</td>
<td>sand</td>
<td>PB</td>
</tr>
<tr>
<td>21</td>
<td>1.20</td>
<td>2.20</td>
<td>80</td>
<td>542</td>
<td>sand</td>
<td>PB</td>
</tr>
<tr>
<td>22</td>
<td>0.80</td>
<td>1.60</td>
<td>100</td>
<td>560</td>
<td>sand</td>
<td>PB</td>
</tr>
<tr>
<td>23</td>
<td>0.70</td>
<td>1.50</td>
<td>100</td>
<td>309</td>
<td>sand</td>
<td>PB</td>
</tr>
<tr>
<td>24</td>
<td>1.15</td>
<td>2.00</td>
<td>53</td>
<td>512</td>
<td>sand</td>
<td>PB</td>
</tr>
<tr>
<td>25</td>
<td>1.15</td>
<td>2.00</td>
<td>60</td>
<td>475</td>
<td>sand</td>
<td>PB</td>
</tr>
</tbody>
</table>

Unit: $D, H$ (m), $\sigma';$ (kPa), PB: Preboring, IE: Inner excavation.

### DESIGN VALUES OF POINT BEARING LOADS

**Design Procedure**

Design values of point bearing loads are evaluated as follows.

**STEP 1:** Using $D, H, \sigma';$ and $N$ as inputs, $P_t, P_s, P_u$ and $P_6$ are calculated by the nomographs.

**STEP 2:** Probability $\alpha$ is set with which design values are less than loading test values. Loading test values are those that will be evaluated if a loading test is carried out in practice. Assuming that the probability distribution of the ratio is normal, the value of $\beta$ is determined, where the ratio is greater than $\mu - \sigma$ with the probability $\alpha$. For
example, if $\alpha$ is 90%, 95%, or 97.7%, $\beta$ is 1.28, 1.64 or 2.0 respectively.

STEP 3: Multiplying the calculated values by $\mu - \beta \alpha$, the design values are obtained.

A Numerical Example

Point load $P_8$ is evaluated where $D=0.8$ m, $H=2.0$ m, $N=50$ and $\sigma'_s=250$ kPa. $N/\sqrt{\sigma'_s}$ is 3.16 and $H$ is 2.5D and $(N/\sqrt{\sigma'_s}, \sigma'_s, D, H)=(3.16, 250, 0.8, 2.5D)$. From the nomographs, when $(N/\sqrt{\sigma'_s}, \sigma'_s, D, H)=(2.0, 200, 0.8, 2.5D)$, $P_8$ is 4.0MN, and when $(N/\sqrt{\sigma'_s}, \sigma'_s, D, H)=(2.0, 300, 0.8, 2.5D)$, $P_8$ is 4.7MN. By interpolation, when $(N/\sqrt{\sigma'_s}, \sigma'_s, D, H)=(2.0, 250, 0.8, 2.5D)$, $P_8$ is 4.35MN. Again using the nomographs, when $(N/\sqrt{\sigma'_s}, \sigma'_s, D, H)=(4.0, 200, 0.8, 2.5D)$, $P_8$ is 4.6MN, and when $(N/\sqrt{\sigma'_s}, \sigma'_s, D, H)=(4.0, 300, 0.8, 2.5D)$, $P_8$ is 5.4MN. By interpolation, when $(N/\sqrt{\sigma'_s}, \sigma'_s, D, H)=(4.0, 250, 0.8, 2.5D)$, $P_8$ is 5.0MN. Using the values in cases of $(N/\sqrt{\sigma'_s}, \sigma'_s, D, H)=(3.16, 250, 0.8, 2.5D)$ is evaluated interpolatively and is 4.73MN. Setting $\alpha$ at 90%, $\beta$ is 1.28. As can be seen in the histograms of $P_8$ in Fig. 10, $\mu$ and $\sigma$ of $P_8$ are 0.95 and 0.17. $\mu - \beta \alpha$ is 0.671. The design load is 4.73MN multiplied by 0.671 and is equal to 3.46MN.

CONCLUSIONS

A new estimation method is proposed for point bearing loads of bored precast piles installed into sandy sup-
porting strata by preboring or by inner excavation. The piles have widened holes at the pile points into which cement milk is poured. The diameter of the widened part is $D$, while the length of the part embedded into a supporting stratum is $H$. SPT N-value is $N$ and effective overburden pressure on the surface of the supporting stratum is $\sigma'i$. Main conclusions on the method are as follows.

a. By finite element method and neural network, we can estimate soil parameters, using loading test results, $D$, $H$ and $\sigma'i$. The soil parameters are angle of internal friction and a parameter relating to stiffness of soil. Nineteen loading tests are analyzed and the soil parameters are obtained.

b. Regression analyses on the soil parameters, $N$ and $\sigma'i$ are carried out and regression lines are obtained.

c. Another neural network is constructed which can calculate load-settlement relations if soil parameters, $D$, $H$ and $\sigma'i$ are given.

d. The latter neural network and the regression lines are combined and nomograph are presented which can calculate $P_1$, $P_2$, $P_3$, $P_4$, $P_5$, and $P_6$ if $D$, $H$, $N$ and $\sigma'i$ are given, where $P_1$, $P_2$, $P_3$, $P_4$, $P_5$, and $P_6$ are the loads at point settlements of $0.01D$, $0.02D$, $0.04D$, $0.06D$ and $0.08D$.

REFERENCES


