MODEL TESTS AND ANALYSES OF Laterally LOADED PILE GROUPS

TORU SHIBATAⁱ⁾, ATSUSHI YASHIMAⁱⁱ⁾ and MAKOTO KIMURAⁱⁱⁱ⁾

ABSTRACT

Lateral loading tests were carried out on model free-headed pile groups. The test piles were embedded in sand which was prepared by the boiling method. Data on group efficiency with pile spacing are presented for comparison with theoretical predictions based on the method developed by M.F.Randolph (1981). The predicted and measured values of group efficiency are generally in good agreement, with a maximum discrepancy of about 30%. Some parametric studies on the behaviour of laterally loaded prototype pile groups are also made using Randolph's equation.

Key words : bearing capacity, deep foundation, horizontal load, load test, model test, pile, pile group (IGC : E 4)

INTRODUCTION

The bearing piles of structures are divided into two categories. One is the so-called active pile which is subjected to an external lateral force at the pile top by unsymmetrical pressure, earthquakes, waves, wind, etc. The other is the passive pile which resists the movements of the surrounding ground (for example, land slide preventive piles). When designing bearing piles, it is extremely important to give consideration to the lateral resistance of the group piles. Unfortunately much remain unknown regarding the problem of lateral resistance as it includes the following complex factors ; the behaviour of the soil surrounded by the piles, the fixed

condition of the pile tops, and the ratio of the load distribution. Judging from the design method presently in use, the effect of group piles has not yet been evaluated quantitatively. For example, in the existing design method for road construction, if the spacing between pile center lines is larger than $2.5d$ (d : pile diameter), the group piles are treated as a set of single piles.

In some instances, there are strict site limitations for construction work done within a city, so that the pre-determined number of piles must be driven into a confined area. Consequently, the spacing between the pile center lines often cannot be kept wider than $2.5d$. And generally speaking, the narrower the spacing between the pile center lines,

ⁱ⁾ Professor, Disaster Prevention Research Institute of Kyoto University, Uji 611.

ⁱⁱ⁾ Instructor, Disaster Prevention Research Institute of Kyoto University, Uji 611.

ⁱⁱⁱ⁾ Instructor, Department of Civil Engineering, Kyoto University, Kyoto 606.

Manuscript was received for review on March 29, 1988.

Written discussions on this paper should be submitted before October 1, 1989, to the Japanese Society of Soil Mechanics and Foundation Engineering, Sugayama Bldg. 4F, Kanda Awaji-cho 2-23, Chiyoda-ku, Tokyo 101, Japan. Upon request the closing date may be extended one month.

Fig. 1. Flow of pile group's study

the greater the reduction in laterally loaded bearing capacity. Although this dilemma is encountered more and more, the question of how to assess the reduction factor of lateral resistance remains unanswered.

Even though problems involving group piles subjected to lateral loading have been dealt with through theoretical research since around 1930, difficulty in verification by prototype tests and the complex behaviour of the ground are said to be new subjects for speculation. Since trends in research activities during the past 50 years have been reviewed in detail by Nishida (1975), they will not be repeated here. To give a general outline of the contents, however, Fig.1 shows the three approaches taken, namely, model tests, prototype tests, and the analytical method.

Prototype tests do produce the most effective and quantitative results, however, there are cost limitations due to the extensiveness of the tests. Model tests are also very effective because for the same purpose and under the same conditions, many factors can be changed. However, in order to apply these test results to the design of prototype group piles, it is necessary that there should exist law of similarity. Consequently, the results of model tests in gravity (1g) only represent qualitative ones. In this study, therefore, model tests which can widely alter the relative rigidity between piles and ground are considered. It stands to reason that if the analytical method can quantitatively explain the results of model

tests under wide relative rigidity (represented by flow © in Fig.1), then the analytical method can be used as a guideline for the actual design (flow ④ in Fig.1).

This paper has been put together with references 6) and 7), and later data. Firstly, concerning the model tests on free-headed pile groups, we investigated how each factor would influence the group pile efficiency and load distribution ratio when we changed various parameters such as the arrangement of the piles, the number of piles, the spacing between pile center lines, and the rigidity of the piles. Secondly, Randolph's method which can account for the behaviour of group piles is introduced as the analytical method. It is researched by comparing the measured values with the predicted ones, with regard to suitability and the applicable range. Furthermore, in order to measure the applicability of the analytical method to actual group piles, several case studies were conducted and a basic design method for the group piles has been considered, about which we shall present a few ideas.

SUMMARY OF RANDOLPH'S ANALYSIS

Randolph's analysis (1981) parametrically reduces the behaviour of piles in an elastic ground using the Finite Element Method. As for the interaction between group piles, Mindlin's second solution is applied in the same way as Poulos' method (1971).

To begin with, for laterally loaded single pile, the following factors are related to the deformation.

(1) External load : lateral load on pile top (H) and bending moment applied to the pile at ground level (M).

(2) Pile material : radius of pile (r_o) and effective Young's modulus of the pile ($E_p = 4(EI)_p / \pi r_o^4$).

(3) Ground (Soil) : rate of increase of the ground's shear modulus (G) with depth (z), $m = \Delta G / \Delta z$, and Poisson's ratio ν .

Expansion of the solution for the lateral response of single pile to deal with group piles is possible through use of the interac-

Fig. 2. Notations used in Randolph's method

(a) ρ_c and G_c , (b) s and β

tion factors proposed by Poulos (1971). When K_s represents the stiffness of a single pile (load divided by displacement), the displacement of the i -th pile in a group of n piles may then generally be written as follows,

$$\delta_i = \frac{1}{K_s} \sum_{j=1}^n \alpha_{ij} P_j \quad (1)$$

where α_{ij} : the interaction factor between the i -th and j -th pile ($\alpha_{ii}=1$), and, P_j : the load on the j -th pile.

Also, for the free-headed pile tops subjected to lateral load (H), the factor (α_H) which increases pile displacement by lateral load, and (α_M) which increases pile displacement for moment loading (M), etc., are defined. These interaction factors are assumed as follows,

$$\alpha_H = 0.5 \rho_c \left(\frac{E_p}{G_c} \right)^{1/7} \left(\frac{r_0}{s} \right) (1 + \cos^2 \beta),$$

$$\alpha_M = \alpha_H^2. \quad (2)$$

When $\alpha_H > 0.5$, however, $1 - (4\alpha_H)^{-1}$ should be used in its place. In this equation, when the critical length of the pile is l_c , the characteristic shear modulus G_c is equal to the value of G^* at a depth of $l_c/2$ (see Fig. 2). Consequently, G_c represents the average value of G^* over the active length of the pile. In addition, parameter ρ_c

reflects the relative homogeneity of the soil rigidity, and is defined (see Fig. 2) as:

$$\rho_c = G^*_{0.25l_c} / G_c. \quad (3)$$

Thus, ρ_c varies from unity for homogeneous soil, down to 0.5 for soil with stiffness proportional to depth. s is the spacing between pile center lines, and β is the angle from the loading direction of the pile (refer to Fig. 2(b)).

The general algebraic equation for the ground displacement of a single pile subjected to lateral load is represented in the following equation,

$$\delta_s = \frac{(E_p/G_c)^{1/7}}{\rho_c G_c} \left[0.27 H \left(\frac{l_c}{2} \right)^{-1} + 0.3 M \left(\frac{l_c}{2} \right)^{-2} \right]. \quad (4)$$

From the above equation, the displacement is governed by the product $\rho_c G_c$ which represents the value of G^* at one quarter the depth of the active length of the pile ($G^*_{0.25l_c}$), and δ_s is inversely proportional to the magnitude of $\rho_c G_c$.

OUTLINE OF THE TESTS

Test Apparatus

Lateral loading tests on model piles were carried out using the apparatus shown in Fig. 3. The soil chamber (height 105 cm, diameter 165 cm) was cylindrical and made of steel. A pulley was attached to the outer wall to allow for lateral loading. The model piles were 80 cm in length and made of aluminum (experiment A) and chloridized-vinyl (experiment B), details of which are shown in Table 1. To measure both the bending moment and shear force of the model

Fig. 3. Sketch of lateral loading apparatus

Table 1. Details of the model piles

Exp.	External diameter (mm)	Wall thickness (mm)	Section area (cm ²)	Length (cm)	Bending rigidity (kgf·cm ²)
A	20	1.6	0.92	80	2.84×10^5
B	22	2.2	1.37	80	2.05×10^4

Exp. A ; Aluminium pipe

Exp. B ; Chloridized-vinyl pipe

piles, 2 pairs of strain gauges (4 in all) were affixed about 8 cm below each pile top. The gauges were covered with epoxy resin in order to reduce the friction between the model piles and the soil, and to prevent the penetration of water.

In order to maintain the condition of free rotation at the pile top, we used universal joints between the steel plates (2 cm in thick) and the pile tops. These joints allowed free rotation in two directions; back and forth, and left and right of the loading direction. Thus, the direction of free rotation corresponded to the loading direction of the group piles at the time they were set.

Model Ground and Pile Arrangement

In order to conduct model tests with accuracy, it is necessary to create a uniform model ground. For this purpose, the following methods are considered.

- 1) Use mechanical compaction or compaction by feet
- 2) Funnel the ground materials through large sieves
- 3) Use the boiling technique for the entire ground and then install the piles

Previously, the tests were conducted using the compacting method (1)), however, since we could not create the same ground conditions for each experiment, it was very difficult to prevent the data from scattering. Therefore, to make the ground as homogeneous as possible this time, the boiling technique (3)) was adopted. The procedure is explained as follows in a)~c).

a) Supply pressure water by a pump from the 4 holes at the bottom of the soil chamber, and boil the model ground.

b) Insert the model piles into the ground gently, and adjust the height of the pile tops

and the direction toward the pulley.

c) Stop the supply of water from the pump, drain the boiled water from the 4 holes at the bottom of the soil chamber, and leave the model ground as it is for 24 hours.

The average values of the void ratio and water content were measured at 4 points in depth (5 cm, 10 cm, 15 cm and 20 cm below the ground surface), and each mean value was 0.76 and 3.1%, respectively. The values for the soil properties of the model ground were as follows: $D_{50}=0.60$ mm, $U_c=3.0$, unit weight= 1.74 gf/cm³, $e_{max}=0.82$ and $e_{min}=0.52$.

After completion of the experiments, cone penetration tests were conducted with a portable cone 5 times at different places in the same model ground. The results are shown in Fig. 4. The dark solid circles show the mean value and the horizontal lines show the range of data.

The arrangement of the model piles consisted of three different types (see Table 2), namely, the Parallel, Series, and Box arrangement piles with respect to the loading direc-

Fig. 4. q_c value from portable cone penetration test for the model ground ($1 \text{ kgf/cm}^2 = 98.1 \text{ kN/m}^2$)

Table 2. Arrangement of piles for model tests

	Arrangement	Number of piles	Ratio of pile spacing s/d	
Exp.A Aluminium pipe	Parallel	2,3,4	2.0,2.5,5.0	Parallel
	Box	4,9,16		Series
Exp.B Chlorized-vinyl pipe	Box	4	1.8,2.3,4,1 6.8,9.1	Box
		9,16	1.8,2.3,4.6

Fig. 5. Lateral loading steps

tion (for the Chloridized-vinyl piles, only Box arrangement piles). The number of piles in each arrangement for the Parallel and Series arrangement piles was 2, 3, and 4, and for the Box arrangement piles was 4, 9, and 16. The spacing between pile center lines (s) was $2.0d$, $2.5d$ and $5.0d$. And for the chloridized-vinyl piles, the spacing was $1.8d$, $2.3d$ and $4.6d$. Hereafter, the experiment using aluminum model piles will be referred to as experiment A, and that using the chloridized-vinyl model piles will be called experiment B.

Methods for Loading and Measuring

Lateral load was applied to the model piles with a loading step of 2 kgf per pile. Bringing the load temporarily back to zero, the reloading points for piles in experiment A were 8 kgf, 16 kgf and 24 kgf, and for experiment B were 2 kgf, 4 kgf, and 6 kgf. As an example, the load cycle for each pile in test A is shown in Fig. 5.

As mentioned above, the measurement items consisted of the value of each strain gauge and that of the dial gauge for the lateral displacement. The free standing length from the ground surface was $h=6.1$ cm for experiment A, and $h=6.9$ cm for experiment B.

TEST RESULTS AND CONSIDERATIONS

Relationship between Load and Displacement, and Definition of Group Efficiency

The lateral loading tests were conducted 4 times for each pile arrangement under the same condition. Single pile tests (64 times for experiment A and 31 times for experiment B) were carried out at the place where the single pile was sufficiently far from the group piles. For reference, the relationship between load and displacement of the Parallel piles in experiment A is shown in Fig. 6. The area surrounded by the broken lines in the figure shows the measurement value from the 4 tests, and the solid line is the mean value of each displacement. According to this figure, scattering of measured lateral displacement is small. We conclude, therefore, that the model ground can be reproduced quite satisfactorily using the boiling technique.

The bearing capacity of the group piles (Q_g) is not equal to the product of the single pile's bearing capacity (Q_s) and the number of embedded piles in the groups (N), namely, $Q_g \neq Q_s \cdot N$. The reduction factor is

Fig. 6. Example of the relation between load and lateral displacement

generally called group efficiency (e), and is represented by the following equation.

$$e = Q_g / (N \cdot Q_s) \quad (5)$$

Group piles have more displacement than a single pile even when the average load of each pile is same. Thus, group efficiency (e) can also be expressed in the following way,

$$e = \delta_s / \delta_g \quad (6)$$

where δ_g = lateral displacement of group piles when the average load of each pile is the same for single pile. In this study, Eq. (6) concerning displacement is adopted.

Fig. 7 shows an actual example of how to calculate group efficiency (e), and represents the relationship between the lateral load and the pile top displacement for single pile and group piles (experiment A, 4×4 Box arrangement piles, $s/d=2.5$). The load for group piles, however, equals the average load per pile. Comparing the single and group piles, the increase for each lateral displacement is

Fig. 7. Definition of group efficiency

defined as δ_s and δ_g , respectively, for the reloading process from 0 kgf to 8 kgf. The group efficiency is calculated as shown in Eq. (6).

From now on, when the group pile efficiency and the ratio of load distribution are calculated, we will use the displacement at the 8 kgf reloading point for experiment A (high rigidity) and that of the 2 kgf reloading point for experiment B (low rigidity).

Ground Constants Using Randolph's Equation

In order to analyze the model tests, it is necessary to determine the ground constants G_0 and $\Delta G/\Delta z$ shown in Fig. 8, and Poisson's ratio ν . Generally speaking, $G_0 \neq 0$ and $\Delta G/\Delta z = 0$ for cohesive soil, and $G_0 = 0$ and $\Delta G/\Delta z \neq 0$ for sandy soil. For the remainder of this paper, we shall refer to the cohesive and sandy soils as C-type and S-type grounds, respectively (Kubo, 1964).

The mean displacement $\delta_s = 1.98$ mm at the 8 kgf reloading point in experiment A is applied to Randolph's equation, assuming Poisson's ratio $\nu = 0.33$ and $\Delta G/\Delta z = 0.3$ kgf/cm³ for the S-type ground and $G_0 = 2.75$ kgf/cm² for the C-type ground (see Table 3). For these two groups of values, it has been assumed that either G_0 or $\Delta G/\Delta z$ is equal to zero, but in actuality, neither $G_0 \neq 0$ nor $\Delta G/\Delta z \neq 0$. Fig. 9 shows the results of Randolph's equation for group efficiencies

Fig. 8. Types of ground and shear modulus

Table 3. Properties of the ground based on a single pile's behaviour

Kinds of experiments		Load (kgf)	δ_s (mm)	G_0 (kgf/cm ²)	$\Delta G/\Delta z$ (kgf/cm ³)
Exp. A	S-type	8.0	1.98	0	0.30
	C-type			2.75	0
Exp. B		2.0	1.50	2.50	0.40

 (1kgf/cm²=98.1kN/m²)

assuming S and C-type grounds, using the above Eq. (6). In this figure, the vertical and horizontal axes represent group efficiency (e) and the ratio of spacing between pile center lines (s/d), respectively. The parameter is the number of piles. From Fig. 9 we can see that even if the displacements of a single pile in the C-type and S-type ground are kept same, the group efficiency of the C-type ground is found to be less than that of the S-type ground.

To further understand the value of constants G_0 and $\Delta G/\Delta z$ used in Randolph's equation in experiment B, the bending moment of a single pile at a depth of $z=13.4$ cm from the ground surface is measured by a strain gauge. And through different combinations of ground constants G_0 and $\Delta G/\Delta z$, the distribution of in-depth bending moment for a single pile is calculated and compared with the mean values of the bending moments measured at $z=13.4$ cm. As a result, when the combination value of (G_0 , $\Delta G/\Delta z$) is equal to (2.5 kgf/cm², 0.40 kgf/cm³), the measured moment is in good agree-

Fig. 9. Types of ground and group efficiency

ment with the calculated one (see Table 3). The ground constants shown in Table 3 will be used in later analyses.

Consideration for Group Efficiency

Following in Figs. 10 and 11, we will show examples of the relationship between group efficiency (e) and the ratio of spacing between pile centers (s/d) (hereafter abbreviated as the relation $e \sim (s/d)$). In each figure, the vertical lines and circular symbols represent the range of values and the mean value from the 4 tests, respectively.

Fig. 10 shows the $e \sim (s/d)$ relation for the 4 Parallel piles in experiment A. According to this figure, the data whose value of group efficiency (e) exceeds 1 are caused by a difference in load distribution, as will be mentioned later. In other words, the average lateral load per pile is 8 kgf, but for some piles the lateral load is less than 8 kgf. There-

Fig. 10. Group efficiency and ratio of spacing between piles (Parallel piles, Experiment A)

Fig. 11. Group efficiency and ratio of spacing between piles (Series piles, Experiment A)

fore, we may assume that load distribution affects group efficiency. Furthermore, when considering the lateral resistance of group piles, besides an increase in displacement due to stress superposition, lateral resistance also increases due to an arching action in front of the Parallel piles in sandy ground. Since the effect of the arching action is more significant than that of stress superposition, group efficiency (e) is believed to exceed 1.

Fig. 11 shows the $e \sim (s/d)$ relation for the 2 Series piles in experiment A. Although the measured values for 2 piles are in good agreement with those obtained with Randolph's equation, values for 3 and 4 piles shows a tendency to be about 30% larger than those from Randolph's equation.

Fig. 12 shows the $e \sim (s/d)$ relation for the Box arrangement piles (3×3 and 4×4 piles) in experiment A. In this figure, besides Randolph's equation, the equation proposed by Tamaki et al. (1971) is also presented. In

Fig. 12. Group efficiency and ratio of spacing between piles (Box arrangement piles, Experiment A)

Fig. 13. Group efficiency and ratio of spacing between piles (Box arrangement piles, Experiment B)

this experiment A, Tamaki's equation tends to estimate much larger group efficiencies than Randolph's.

In the same way, Fig. 13 shows the $e \sim (s/d)$ relation for experiment B. According to this figure, Randolph's theoretical curve using the ground constants (Table 3) estimated from the measured displacement and bending moment of the single pile can quantitatively account for the test values even if the pile rigidity changes. In the case of the 4×4 Box arrangement piles, Tamaki's equation can also evaluate group efficiency quantitatively.

So far we have investigated group efficiency placing special importance on the spacing between piles, but generally speaking, it may be said that the relative rigidity of the piles and the ground also have an effect on the group efficiency. Therefore, a discussion on relative rigidity follows.

Firstly, effective Young's modulus E_p is used for the rigidity of piles. The value of shear modulus $G^* = G(1 + 3\nu/4)$ at a quarter of the depth of the critical length of the pile is used for the ground rigidity, and the above-mentioned shear modulus is shown in a simplified way, as G_s . In other words,

$$G_s = G^*_{0.25lc} \quad (7)$$

Fig. 15. Comparison between measured and calculated group efficiency

(a) Comparison with Randolph's equation

(b) Comparison with Tamaki's equation

Fig. 14. Group efficiency and relative rigidity

According to Randolph's equation, since the displacement of laterally loaded pile top δ_s (lateral displacement of the pile at ground level) is inversely proportional to G_s , G_s is

selected as one of the ground constants.

In the above sections, two different types of experiments (A and B) have been explained, however, here we shall define the results of reference 2) as experiment C. For model tests in experiment C, aluminum piles were used in a compacted model ground. The values of E_p/G_s decrease in the following order; experiment C > experiment A > experiment B (see Fig. 15).

Fig. 14 shows the relationship between group efficiency and relative rigidity. Test results as well as Randolph's and Tamaki's proposed equations are shown. Fig. 14 (a) is the Box arrangement case (3×3 piles), where $s/d=2.5$, and Fig. 14 (b) also for the Box arrangement case (4×4 piles) shows $s/d=2.5$. Test results and Randolph's equation show that along with an increase in relative rigidity, group efficiency tends to decrease. Since s/d is equal to 2.3 for the plotted value in experiment B (see Table 2), it is estimated that the e value of $s/d=2.5$ is larger than that of $s/d=2.3$.

Tamaki's experimental equation, on the other hand, is represented by the following function,

$$e = f(s/d, FC, m, n) \quad (8)$$

where, FC : fixed condition of pile top

m : number of columns of piles

n : number of rows of piles

In this case, therefore, the effect of relative rigidity cannot be evaluated by Eq. (8). Even if E_p/G_s changes, group efficiency (e) is constant, and the equation does not correspond to the trend found in the model test results.

In Fig. 15 (a), the results of Box arrangement pile tests (the mean value of the 4 experiments) conducted with three types of relative rigidity are compared with Randolph's equation. The vertical and horizontal axes represent the calculated and measured values of group efficiencies, respectively. According to this figure, we conclude that Randolph's equation can estimate the values of group efficiency with a maximum discrepancy of about 30% in any case. A comparison with Tamaki's equation is shown in

Fig. 15 (b). When E_p/G_s is large ($\blacktriangle$ symbol in figure), the predicted and measured values of group efficiency are not in good agreement (a maximum discrepancy of about 60%). Since the relative rigidity between piles and the ground must be considered in order to evaluate the group efficiency, Randolph's equation is thought to be quite valuable.

Consideration for the Load Distribution Ratio

Figs. 16 and 17 represent the test results (mean value of the 4 measured values) for Parallel (4) and Box (4×4) arrangement piles. The shear force of the pile top of pile No. 1 is used to normalize the shear forces for the other piles. The broken lines in the figures are the results calculated with Randolph's equation. Since it assumes the ground as an elastic material, the ratio of load distribution for piles in a symmetrical position (for example; Nos. 1 and 4, Nos. 2 and 3, Nos. 5 and 8, and Nos. 6 and 7 in Fig. 16) are calculated equally. However, the model test values (the Box arrangement piles in particular) do not represent this kind of symmetric behaviour at all. The piles positioned in back (Nos. 3 and 4) with respect to the loading direction are subjected to a much lesser load than those in front (Nos. 1 and 2). In addition, the ratio of spacing between pile center lines tends to

Fig. 16. Comparison of load distribution ratio and Randolph's equation (Series 4 piles)

Fig. 17. Comparison of load distribution ratio and Randolph's equation (Box arrangement 4x4 piles)

become larger, and lateral load is distributed to each pile equivalently.

When comparing values for $s/d=1.8$ and $s/d=2.3$ in Fig. 17, we see that $s/d=1.8$ gives more uniform load than $s/d=2.3$. From test results, we have found that this is due to the fact that when the spacing between pile center lines is too small, the soil surrounding the piles behaves in the same way as the piles themselves.

CASE STUDIES USING RANDOLPH'S ANALYTICAL METHOD

In this section, parametric studies are conducted with Randolph's method on full scale group piles being used in the construction of a pier foundation of a highway bridge on real ground. In the group pile research approach shown in Fig. 1, since Randolph's equation can estimate the behaviour of model tests quantitatively (flow ©), it is applicable

Fig. 18. Pier foundation in case study ($1 \text{ kgf/cm}^2 = 98.1 \text{ kN/m}^2$)

Fig. 19. Group efficiency for fixed condition of pile head and N value of the ground

to the prototype group piles along flow © shown in Fig. 1.

Case studies are conducted by changing and analyzing the following parameters; the ground condition (C and S-types), the spacing between pile center lines, the number of piles, the arrangement of the piles, and the fixed condition of the pile tops. A few of the results are given below.

Case Study Procedures

Firstly, the full scale piles are assumed to be made of concrete and have the dimensions of $d=1.5 \text{ m}$ in diameter and $l=30 \text{ m}$ in length, and have a effective Young's modulus of $E_p=2.7 \times 10^5 \text{ kgf/cm}^2$ (see Fig. 18).

Secondly, in order to use Randolph's equation, it is necessary to determine the ground parameter G_0 for the C-type ground and $\Delta G/\Delta z$ for the S-type one. Shear modulus G is estimated here from the N value, and

Fig. 20. Arrangement of piles under limited footing area
(lateral load is 120 tf in any case)

according to reference 9) the relationship between Young's modulus E (kgf/cm²) and the N value can be expressed as $E=7N$. Assuming Poisson's ratio $\nu=0.33$, the shear modulus can then be calculated by the following equation.

$$G=7N/\{2(1+\nu)\}=2.69N \text{ (kgf/cm}^2\text{)} \quad (9)$$

Results and Considerations of Case Studies

Fig. 19 shows the $e \sim (s/d)$ relation for 4×3 piles using the N value and the pile top fixed conditions as parameters. According to this figure, the larger the ground rigidity is (in other words, since E_p is under the same conditions, E_p/G_s is small), the larger efficiency (e) becomes. Since the fluctuation of E_p/G_s is small ($1.12 \times 10^4 \sim 3.35 \times 10^4$), the value of e does not change much as shown in Fig. 14.

Furthermore, group efficiency (e) of the fixed-headed piles increases 20~30% more than that of the free-headed piles. As it is not easy, however, to determine the fixed condition of the actual group piles, the actual conditions are simulated between the free-headed and fixed-headed ones.

Next, considering the case that there are limitations of the footing area and the lateral load acting on the footing is evident, the behaviour of the group piles should be investigated.

The area for pile construction is now assumed as 12.75 m $\times$ 9.0 m (as shown in Fig. 20), and the pile foundations planned

for design under the condition that the N value=6 for the C-type ground with a lateral load of 120 tf. Numerous cases with various numbers of piles and pile arrangements are considerable, but for the pile foundation shown in Fig. 20, group efficiency (e), group pile displacement δ_g , and the maximum lateral load per pile are calculated. In this case, the ratio of spacing between pile center lines for 4×3 piles corresponds to $s/d=2.5$, and in all other cases $s/d > 2.5$.

To calculate the group efficiency, the mean load per pile is determined to be 120 tf. Secondly, the displacement δ_s of a single pile acting under the mean load is estimated from the single pile displacement under a 10 tf lateral loading condition. Thus, group efficiency is calculated as $e=\delta_s/\delta_g$.

In the manual presently used for road bridges (abbreviated as road manual), the way to decrease group efficiency in consideration of the spaces between pile center lines, is to multiply the coefficient of horizontal subgrade reaction k value by the following revised coefficient μ (road manual, 1980).

$$\mu=1-0.2(2.5-s/d) \quad (\text{where, } s/d < 2.5) \quad (10)$$

Practically speaking, even if the ratio of spacing between pile center lines is larger than 2.5, there is no problem in using the k value as it is for single piles in the above equation.

Based on the above, a comparative example of cases using Randolph's equation and the

Fig. 21. Comparison between Randolph's equation and the design method in the road manual

road manual's design method for prototype piles is shown in Fig. 21. According to Figs. 21 (a), (b) and (c), the following items are pointed out.

1) For group efficiency (e) in Fig. 21(a), according to the road manual, even if the number of piles increases, $e=1.0$ because of the condition that $s/d > 2.5$. In Randolph's equation, however, when the number of piles increases, the decrease in group efficiency is remarkable (For reference, group efficiency (e) in Tamaki's method for 12 piles is situated about mid-way between both methods.).

2) As for the displacement of group piles δ_g in Fig. 21 (b), δ_g nearly decreases in an inversely proportional manner to the number of piles according to the road manual. δ_g hardly changes at all, however, according to Randolph's equation. Consequently, compared with the road manual, Randolph's equation estimates 1.5 (4 piles) to 4 times

(12 piles) larger displacement.

3) Fig. 21 (c) shows the maximum load per pile. Since Randolph's equation can consider the load distribution ratio for each pile, it can thus calculate a much larger value than the road manual.

The above are only a few examples of case studies performed. It should be noted that the results of investigations on (1) varying the N value widely (from 3 to 50), and (2) the 2 different kinds of ground (S and C-types), show the same qualitative characteristics as summarized above in 1)~3).

To sum things up a bit, we can say that since group efficiency is not considered in the existing design method when the ratio of spacing between pile center lines s/d is larger than 2.5, the amount of lateral displacement of the group piles is held down to a allowable value by increasing the number of group piles. We believe it is necessary, therefore, to consider a new method for pile groups.

CONCLUSION

Lateral loading tests were carried out changing several kinds of the model pile parameters, namely, the spacing between pile center lines, the number of piles, the arrangement of the piles, and the rigidity of the piles. The pile tops were all set to rotate freely. Since the model ground was created by the boiling technique, reproduction of a homogeneous ground was accomplished quite satisfactorily. From each type of measured value, a comparative investigation on group efficiency was made taking notice of the displacement of the pile tops.

The theoretical method used is based on Randolph's method. In this method, the elastic parameters of the ground are estimated from lateral loading tests on single piles. Thus, while applying the above estimated values and introducing the interaction factor (based on Mindlin's second solution), we attempted to obtain the group efficiency. For the tests in which the relative rigidities between piles and ground were changed,

it was found that the values of group efficiency predicted by Randolph's equation can estimate the measured ones with a maximum discrepancy of about 30%.

Furthermore, the case studies were conducted with Randolph's equation using prototype group piles. As a result, a large discrepancy was found between Randolph's method and the existing road manual's design method for group efficiency and the displacement of pile tops. It is thought that the road manual tends to sway a little to the dangerous side. In other words, since the road manual ignores group efficiency when the ratio of spacing between pile center lines is more than 2.5 (when $s/d > 2.5$), and simply deals with this occurrence by increasing the number of piles (to hold the lateral displacement down to the allowable value), we conclude that there remains much room for improvement and re-investigation of the existing method.

REFERENCES

- 1) Association of Japanese Road (1980) : Manual of Road Bridge and Its Explanation (IV), p.279 (in Japanese).
- 2) Kubo, K. (1964) : "A new method for the estimation of lateral resistance of piles," Report of the Port and Harbour Research Institute, Vol.2, No.3, pp.1-37 (in Japanese).
- 3) Nishida, Y. (1975) : "Laterally loaded bearing capacity of pile foundation...references and materials, and explanation of research...", Association of Steel Piles (in Japanese).
- 4) Poulos, H. G. (1971) : "Behaviour of laterally loaded piles II—pile groups," Proc. ASCE, Vol. 97, SM 5, pp.733-751.
- 5) Randolph, M. F. (1981) : "The response of flexible piles to lateral loading," Geotechnique, Vol. 31, No.2, pp.247-259.
- 6) Shibata, T., Yashima, A. and Terada, N. (1983) : "Model test of laterally loaded pile groups (1)," Disaster Prevention Research Institute Annuals, No.26 B-2, pp.97-110 (in Japanese).
- 7) Shibata, T., Yashima, A. and Kimura, M. (1984) : "Model test of laterally loaded pile groups (2)," Disaster Prevention Research Institute Annuals, No.27 B-2, pp.77-85 (in Japanese).
- 8) Tamaki, O., Mihashi, K. and Imai, T. (1971) : "Horizontal resistance of a pilegroup subjected to lateral load," Proc. JSCE, No.192, pp.79-89 (in Japanese).
- 9) Uto, K. (1967) : Ground Sounding for Foundation, Foundation of Structure, Kanto-Branch of Japan Society of Civil Engineers, p.46 (in Japanese).