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Lateral resistance of standing pipes

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ABSTRACT: This paper investigates the lateral resistance behavior of the open end type steel pipe piles with a diameter of less than twenty centimeters, embedment depth three meters or less and characteristic value three or less, being obtained from field and one seventh scale model lateral loading tests. As a result, it was considered likely that the lateral subgrade reaction was proportional to the lateral displacement raised to five tenth power and that the coefficient of lateral subgrade reaction was reversely proportional to the diameter.

1 INTRODUCTION

Many studies have been made concerning the lateral resistance of a pile. Nevertheless, few studies have been made concerning the open end type steel pipe pile with a diameter of less than twenty centimeters, embedment depth three meters or less and characteristic value three or less (hereinafter referred to as the pile), whose lateral resistance behavior has not been clarified, accordingly. The present report has an objective of clarifying the lateral resistance behavior of the pile (The Japan Road Association 1980).

The lateral resistance of a pile is a combination of its resistance to bending and the lateral subgrade reaction produced according to a lateral displacement. And it is defined in Equation 1 (Reese and Desai 1977).

$$EI\frac{d^4y}{dx^4} + D\cdot p(x,y) = 0 \qquad (1)$$

EI: flexural stiffness (unit:kgfcm^2 or Nm^2)
y: lateral displacement (unit:cm)
x: embedment depth (unit:cm)
D: diameter (unit:cm)
p: lateral subgrade reaction (unit:kgf/cm^2 or N/m^2)

The study reported herein, therefore, was made concerning the lateral resistance behavior of the pile, based on Equation 1. To this end, those piles which are really applied to the foundation of ancillaries to a road were subjected to the field single pile lateral loading test and to the one seventh scale model lateral loading test on both single and grouped piles.

2 OUTLINE OF LATERAL LOADING TEST

2.1 Field lateral loading test of the pile (Komatsu, Kaneko, Niiro and Kuribayashi 1990)

A metal strain gage was welded to the pile on the internal surface. And this pile was drive into three types of the ground on a percussion basis. Then, a static lateral load was applied. For loading method, a unidirectional multi-cycle load was applied at a loading height of seventyfive centimeters from the ground surface. Table 1 shows the specifications of the pile employed for testing. And Figure 1 shows an example of the test setup. Figures 2 and 3, moreover, illustrate a distribution of Standard Penetration Values on the ground where testing was conducted, and an example of load application patterns, respectively.

Table 1 The specifications of the pile.

·diameter D (unit:cm)	16.52,13.98,10.16
·thickness t (unit:cm)	0.5,0.45,0.32
·stiffness EI (unit:$\times 10^9$kgfcm^2)	1.697,0.920,0.252
·embedment depth L (unit:cm)	200.0,100.0,50.0
·loading height h (unit:cm)	75

Note: To obtain values in SI one should use the conversion as follows:
1kgf = 9.80665N, 1tf = 9806.65N, 1kgf/cm^2 = 98066.5N/m^2

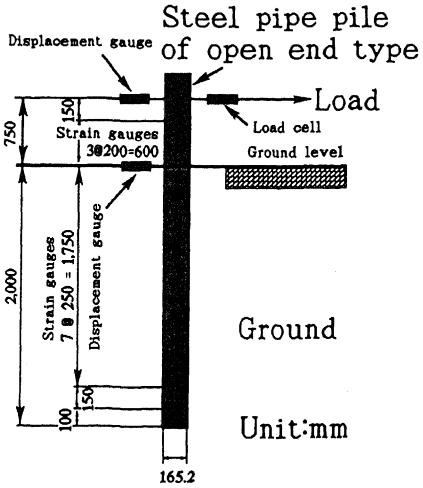


Figure 1 An example of the test setup.

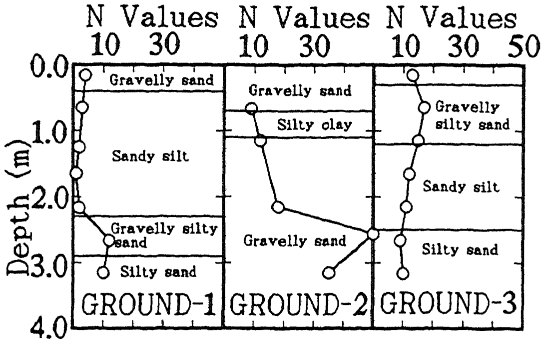


Figure 2 The distribution of Standard Penetration Values on the ground.

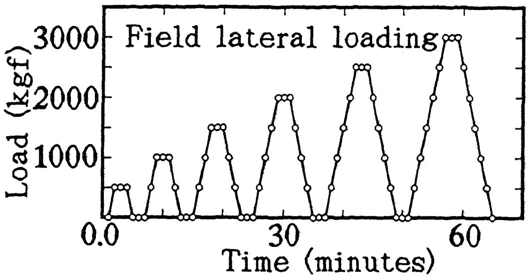


Figure 3 An example of load application patterns.

2.2 Lateral loading test of the one seventh scale model pile (Niiro, Komatsu and Kuribayashi 1992)

The one seventh scale model pile was made by the use of a similarity law so that it would have a bending strain equal to that of the pile used for the field lateral loading test. Since the similarity law requires a geometrical resemblance and an equal similarity ratio of inertia force and shearing stress, it may be defined under Equation 2.

$$\frac{\rho_p \cdot l_p^3 \cdot \alpha_p}{\rho_m \cdot l_m^3 \cdot \alpha_m} = \frac{E_p \cdot \varepsilon_p \cdot A_p}{E_m \cdot \varepsilon_m \cdot A_m} \qquad (2)$$

ρ_p, ρ_m: density (unit:kg/cm^3)
α_p, α_m: loading acceleration (cm/sec^2)
$\varepsilon_p, \varepsilon_m$: bending strain
l_p, l_m: length (unit:cm)
E_p, E_m: modulus of elasticity(unit:kgf/cm^2 or N/m^2)
A_p, A_m: sectional area (unit:cm^2)
Note: Subscript p show the pile and subscript m show the scale model pile.

With acceleration ignored, the length similarity ratio was taken for one seventh.

The one seventh scale model pile was made of hard polyethylene vinyl chloride, to the external surface of which a strain gage was attached and coated with silicone. The ground used for the lateral loading test was made of the silty sand compacted every ten centimeters in a soil tank. For loading, a unidirectional multicycle loading method was used. An example of the test setup is illustrated in Figure 4 while Table 2 indicates the scale model pile specifications. Figure 5 shows the load pattern involved.

Table 2 The scale model pile specifications.

·diameter	D	(unit:cm)	3.8
·thickness	t	(unit:cm)	0.4
·stiffness	EI	(unit:kgfcm^2)	1.873×10^5
·embedment depth	L	(unit:cm)	28.6
·loading height	h	(unit:cm)	10.7

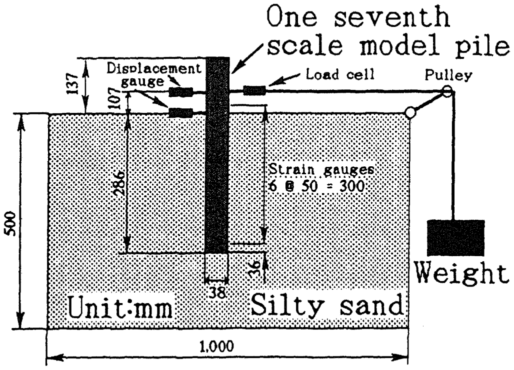


Figure 4 An example of the test setup.

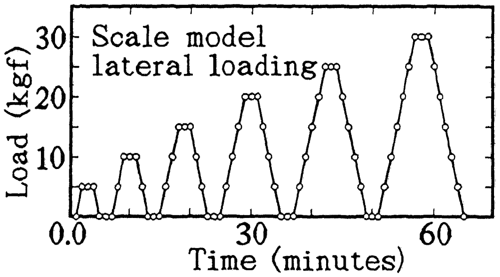
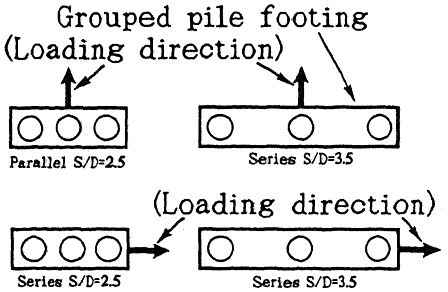


Figure 5 An example of load application patterns.



Note: S/D: pile center space ratio
S: spacing between pile centrelines
D: pile diameter

Figure 6 The shape and loading direction of grouped pile footing.

For the number of scale model piles per group, two and three were grouped in each of the loading direction so called series and of the direction rectangular to the loading one so called parallel. In a group, the piles were set to two center space ratios, i.e. 2.5 and 3.5. Figure 6 shows the shape and loading direction of grouped pile footing.

3 TEST RESULTS AND CONSIDERATION

3.1 Lateral resistance behavior of the single pile (Shinohara and Kubo 1961, Kubo 1966)

1. Relationship between lateral load and displacement
Figure 7 shows a relationship between lateral load and displacement at ground level. From the Figure 7, it may be gathered that the pile residually displaced when unloaded and that the pile showed a small displacement and an elastic behavior when loaded.

2. Relations among pile bending moment, displacement and subgrade reaction
A bending moment was obtained from Equation 3.

$$Mx = \frac{\varepsilon \cdot EI}{W} \qquad (3)$$

Mx: bending moment (unit:kgfm or Nm)
ε : bending strain measured by strain gauges
W: edge distance from neutral axis (unit:cm)
EI: flexural stiffness (unit:kgfcm^2 or Nm^2)

A value of the bending strain on the compression side was used. For edge distance, moreover, a neutral axis was obtained from the strains on both tension and compression sides to take the distance on the compression side. Figures 8(a) through 8(h) show the distribution of bending moments in the pile. From the Figures referred to above, it may be gathered that a discrepancy of embedment depth, pile diameter and ground type had some effects.

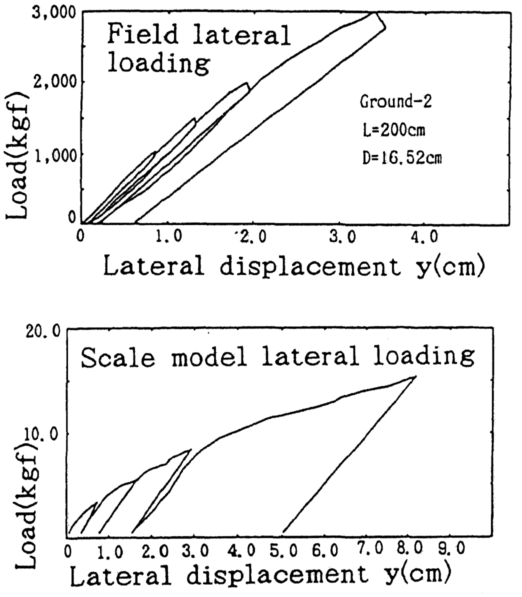


Figure 7 The relationship between lateral load and displacement.

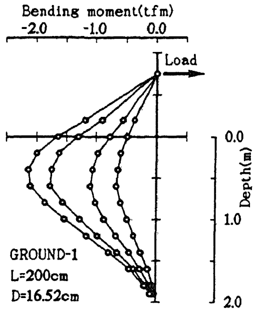


Figure 8(a) The distribution of bending moments.

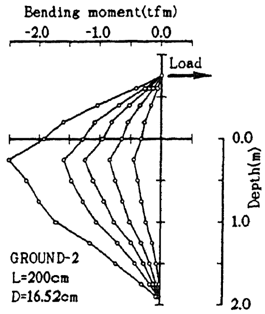


Figure 8(b) The distribution of bending moments.

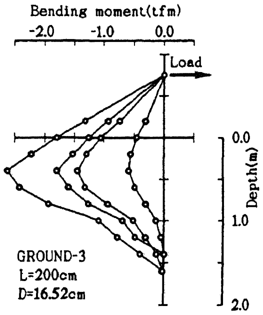


Figure 8(c) The distribution of bending moments.

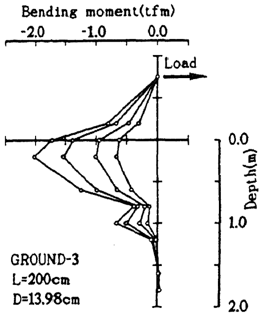


Figure 8(d) The distribution of bending moments.

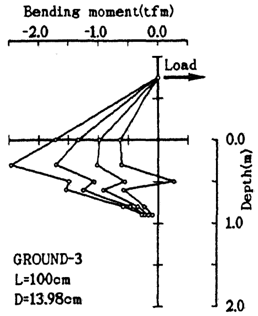


Figure 8(e) The distribution of bending moments.

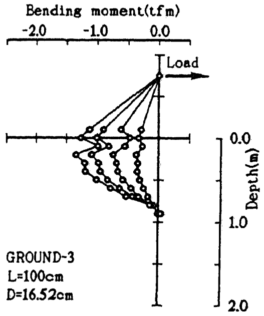


Figure 8(f) The distribution of bending moments.

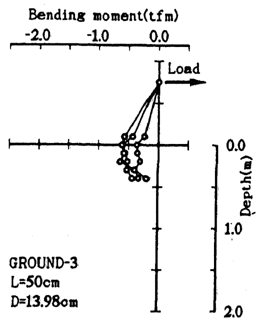


Figure 8(g) The distribution of bending moments.

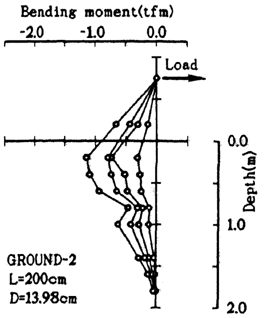


Figure 8(h) The distribution of bending moments.

Equations 4, 5, 6 and 7, moreover, allow us to obtain the shearing stress, lateral subgrade reaction, rotation angle and displacement, respectively. Constants A and B in Equations 6 and 7 were determined, based on the displacements really measured.

$$Q = \frac{dMx}{dx} \quad (4)$$

$$p = \frac{1}{EI} \cdot \frac{d^2Mx}{dx^2} \quad (5)$$

$$\theta = \frac{1}{EI} \cdot \int Mxdx + A \quad (6)$$

$$y = \frac{1}{EI} \cdot \int \int Mxdx^2 + A \cdot x + B \quad (7)$$

Q: shearing stress (unit:kgf or N)
θ: rotation angle (unit:rad)
A and B: constant

Figure 9 shows the example distributions of bending moment, lateral displacement and subgrade reaction.

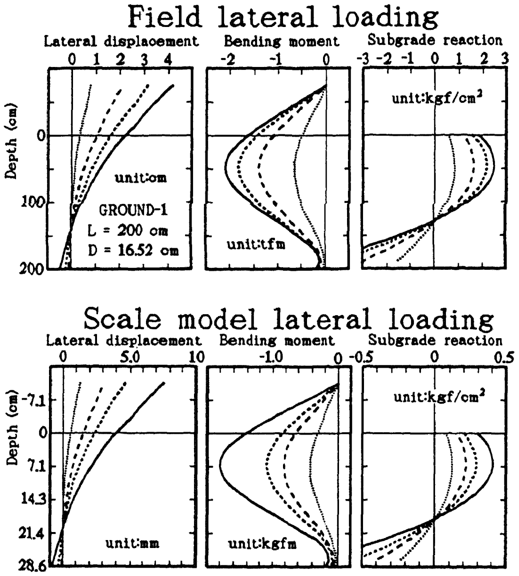


Figure 9 The example distributions of bending moment, lateral displacement and subgrade reaction.

3. Relationship between subgrade reaction and displacement

Figure 10 shows the relationship of the subgrade reaction obtained under Equation 5 with the lateral displacement obtained under Equation 7.

Since both had a linear relation capable of being approximated, we may gather that it applies to the principles of the *non-linear elastic subgrade reaction* method. A gradient of the line in the Figure 10, therefore, turns out an index and it is proportional to the displacement of pile raised to five tenth power. From this, it may be gathered that Equation 8 of Hayashi and Miyajima 1963 is applicable.

$$p = Kc \cdot y^{0.5} \quad (8)$$

Kc: lateral subgrade reaction coefficient

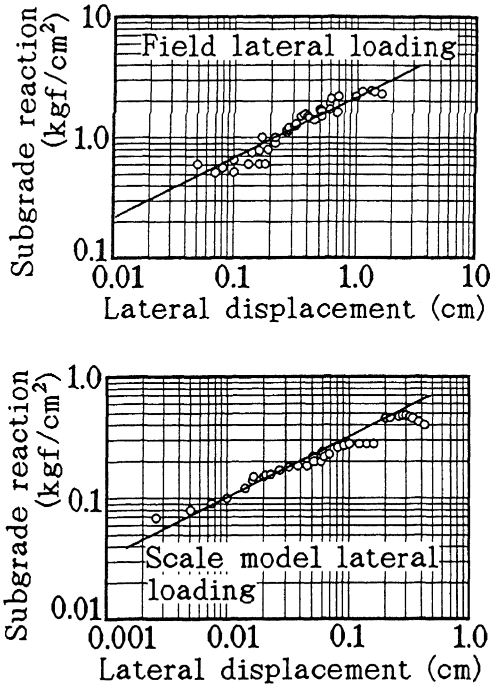


Figure 10 The relationship between the subgrade reaction and the lateral displacement.

4. Lateral subgrade reaction coefficient

The pile with such a small diameter as reported herein has its lateral subgrade reaction coefficient vary with the pile diameter as shown in Figure 11.

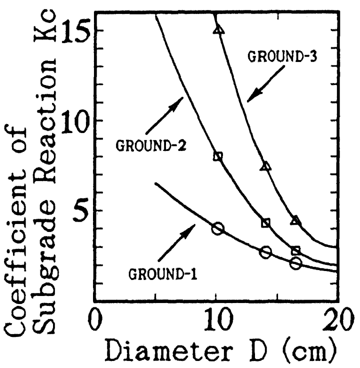


Figure 11 The relationship between lateral subgrade reaction coefficient and pile diameter.

Figure 12 shows a displacement of the pile on the ground surface owing to the discrepancies of lateral subgrade reaction coefficient, pile diameter and pile embedment depth. Figure 12 has linearly approximated the values obtained in testing. From the Figure 12, it may be that a pile with a small diameter on the hard ground would scarcely displace and that a pile with a large diameter on the soft ground would displace remarkably.

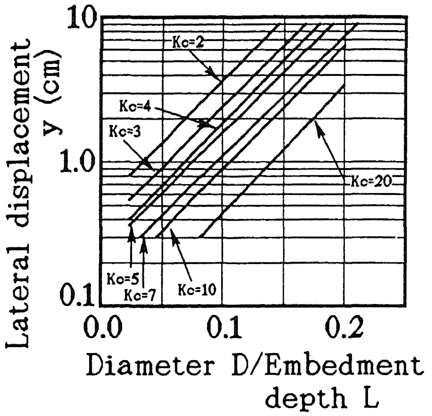


Figure 12 The relationship among lateral displacement, subgrade reaction coefficient, pile diameter and embedment depth.

3.2 Lateral resistance behavior of grouped piles (Randolph 1981)

1. Distribution of bending moments and subgrade reactions

Figures 13(a), 13(b), 13(c), 14(a), 14(b), and 14(c) show the distribution of bending moments and subgrade reactions.

From Figures 13(a) and 13(c), it may be gathered that piles had an identical tendency in their bending moment distribution even if they had a pile center space ratio differ. From Figures 13(b) and 13(c), furthermore, it may be gathered that the bending moment on the ground surface has a size differ among the piles differently arranged. A group of the piles arranged in parallel with the loading direction as shown in Figure 13(b) showed a bending moment distribution with a tendency identical with that for the bending moment distributions of single piles as shown in Figures 8(a) through 8(h). A group of the piles arranged in series with the loading direction as shown in Figure 13(c) had a bending moment go zero on the ground surface.

The grouped pipes shown in Figures 14(a), 14(b) and 14(c) had a subgrade reaction distribution similar to that for single piles as shown in Figure 9, with the piles at the center showing a lower subgrade reaction level than that outwards.

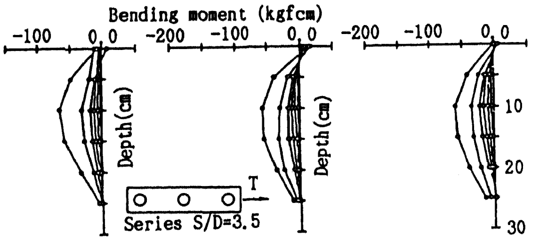


Figure 13(a) The distribution of bending moments.

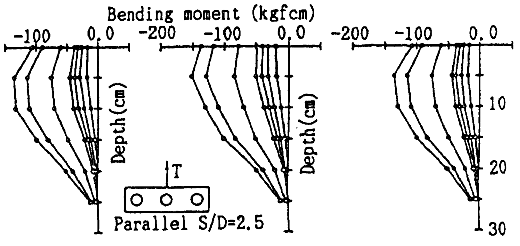


Figure 13(b) The distribution of bending moments.

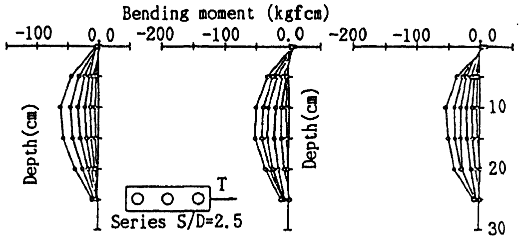


Figure 13(c) The distribution of bending moments.

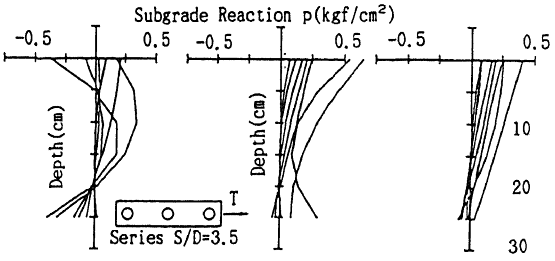


Figure 14(a) The distribution of subgrade reactions.

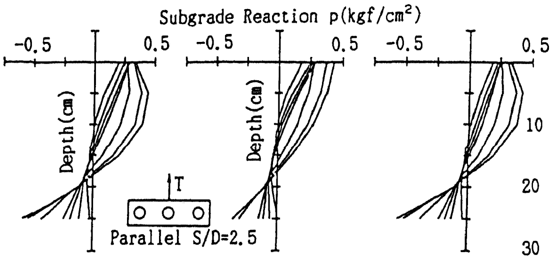


Figure 14(b) The distribution of subgrade reactions.

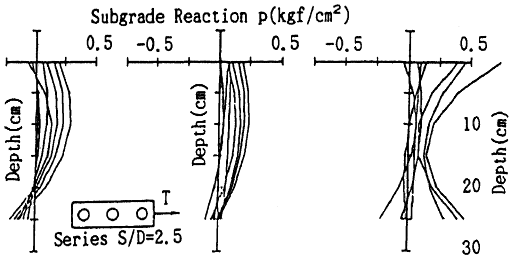


Figure 14(c) The distribution of subgrade reactions.

2. Lateral load share (Kimura, Shibata and Yashima 1987)
Figure 15 shows the ratio at which the lateral load was shared by each pile, with that for a pile on the front reckoned as 1.0.

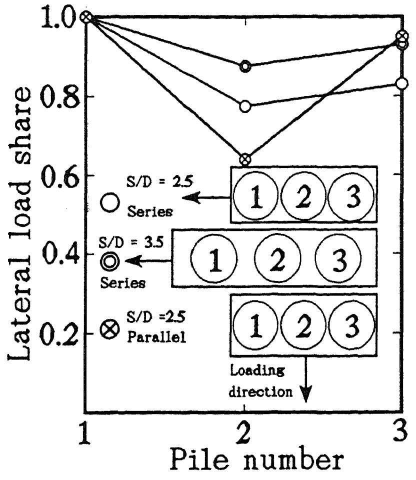
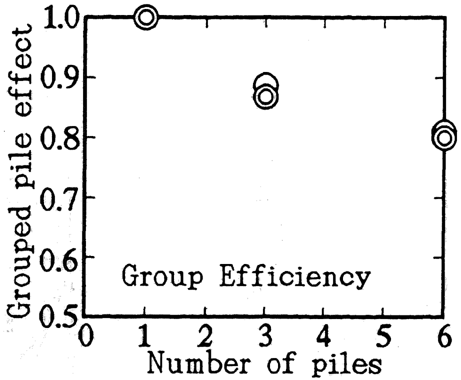


Figure 15 The lateral load share.

From Figure 15, it may be gathered that Piles No.1 and No.3 arranged outwards shared a larger lateral load than that of Pile No.2 arranged the center. It may be gathered, moreover, that Pile No.2 the center shared the lateral load at a higher ratio as arranged in series with the loading direction than that as arranged in parallel.

3. Grouped pile effect
The grouped pile effect relating to a displacement of piles is defined under Equation 9 (Kimura, Shibata and Yashima 1987).

$$\text{Grouped pile effect} = \frac{\text{Displacement of single pile against constant load}}{\text{Displacement of grouped piles relative to constant load} \times \text{number of piles}} \quad (9)$$



.Figure 16 The relationship between grouped pile effect and number of piles.

Figure 16 shows the grouped pile effect obtained from the lateral loading test of one seventh scale model pile. From Figure 16, it may be gathered that a grouped pile effect was generated.

4 CONCLUSIONS

A study was made concerning the lateral resistance behavior of the open end type steel pipe piles, being obtained from field and one seventh scale model lateral loading tests. As a result, the following could be obtained.

1. In both field and one seventh scale model tests, the bending moment did not turn out zero within a range of pile embedment depths. Since a displacement of piles could be linearly approximated, moreover, they might beclassified into a short pile.
2. Results of the one seventh scale model test showed a relation of similarity to the field test results.
The non-linear elastic subgrade reaction method was application to both, accordingly.
3. The lateral subgrade reaction coefficient was reversely proportional to the pile diameter.
4. The equation of Hayashi and Miyajima 1963 was applicable, irrespective of the ground type.
5. A group of piles arranged outwards shared a higher ratio of lateral loads than those the center. And the piles the center shared a higher ratio of lateral loads as arranged in series with the loading direction than that as arranged in parallel. The higher the pile center space ratio, moreover, the more uniformly the load would be distributed to each pile. Besides, a grouped pile effect would arise, accordingly.

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