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SIMILARITY CONDITIONS FOR LATERAL LOAD TEST ON MODEL PILE FOUNDATION WITH LARGE DEFORMATION IN 1G GRAVITATIONAL FIELD

Junji HAMADA[1], Tomio TSUCHIYA[2]

SUMMARY

The necessary similarity conditions between the model and the prototype, considering the ultimate strength of the piles and the ultimate shear strength of the soil, are presented for the model tests in 1g field. The proposed similarity is derived based on an equilibrium of the strain of the pile and the soil at the ultimate stage for quasi-static loading test. In order to taking into account the effect of the failure of the pile and the soil, the similarity of the model test in three situations which are when the soil failed, when the pile failed and when both the soil and the pile failed are suggested. The following assumptions are made. When the soil failed, the ultimate subgrade reaction of the cohesionless soil acted on the pile is in proportion to an effective confining pressure. The proportional relationship between the model and the prototype for flexural rigidity and longitudinal rigidity of the pile are assumed. When the pile failed, same material and same ratio of thickness to diameter between the model and the prototype must be required. When both the pile and the soil failed, the above similarity conditions are required at the same time.

INTRODUCTION

It has been reported that the pile foundation damages were observed during the 1995 Hyogo-ken Nanbu Earthquake([1],[2]). Consequently, after that, a lot of experimental studies have been greatly conducted to reveal the mechanism of the fracture of the piles. Recently, the interaction experiments that the piles and soil failed have been carried out by using a large scale soil container (Tamura[3], Tsuchiya[4]). And large deformation experiments like as causing the pile fracture have been conducted to confirm the mechanism of a ductility of steel or reinforced concrete piles. Many confirmation experiments are required even if the seismic deformation method is introduced for the seismic design. And also, more accuracy improvement of the seismic design is urgently hoped. Hence, it is important to establish test procedures and techniques to reproduce the behavior of an actual soil-pile-structure system during earthquake. The large scales laminar shear box that is able to handle a large model is effective for raising

[1] *Associate Chief Researcher, Research and Development Institute, Takenaka Corporation, Chiba, Japan*
Email: hamada.junji@takenaka.co.jp
[2] *Chief Researcher, Research and Development Institute, Takenaka Corporation, Chiba, Japan*

the accuracy to the fracture mechanism of a pile. There have already conducted some experiments for a single steel pile, a single RC pile and group RC piles with dry sand or liquefied sand.

However, there is not a change with respect to the fact in a model scale test and it is not able to do a cofining pressure on a model sand equally to the one of a real soil because in 1g gravitational field. When the piles and the soil are fractured, previous similarities are not enough (Hamada[5]). In this paper, the similarity conditions, which is perceived to ultimate strength of the pile and ultimate yield of the soil between model and prototype, is proposed for large deformation tests. In addition, the approximate similarities are expanded and simulation studies are conducted by beam-spring model.

PREVIEW OF SIMILARITY LAWS FOR STRUCTURE MODEL OR FOR SOIL MODEL

Similarity for a structure

For a supper structure or a pile foundation's model test without soil, a parameter of a bending modulus is enough for similarity in linear region in case that a bending exercise of pile is dominant. Also, correlation between curvature and bending moment of the pile must be similar between model and prototype in non-linear region. In generally, in case of only structure without soil, scaling model tests could be carried out "without straining" by using same materials of real structure. "Without straining" means the vertical scaling factor is same with horizontal scaling factor.

Similarity for a soil

For scaling model tests with soil, the similarity law had composed in attention to decreasing of the soil shear modulus and increasing damping ratio for soil strain level. Overburden pressure at the model soil is smaller than at the prototype in 1g gravitational field.

Rocha[6] had developed the similarity law for the soil in static condition in attention to these soil effective stress feature in 1 G. Also, Kagawa[7], Kokushou[8] and Iai[9] had derived the similarity law for vibration tests in 1 G with soil. Kazama[10] had presented the similarity in any gravity fields for the centrifuge tests.

These similarity ideas are consisted of the thought that the soil shear modulus over initial shear modulus (G/G_0) decrease with the strain divided by confining pressure to the 0.5-0.6th power ($\gamma/\sigma^{0.5\sim0.6}$) in the experiments at various confining pressure. This similarity is used to the experiments of the interaction of soil and structure.

FAILURE SIMILARITY

In this section, we point out necessary similarity conditions during fracture of soil or piles. Rocha's assumptions are not applicable to the ultimate state of the stability of soil, structure and foundation. The proposed similarity is derived for the failure tests of both pile and soil in 1 g gravitational field. A number of these tests has been increasing. Fracture of the soil relay on a confining pressure under assumption that a distribution of the ultimate subgrade reaction is proportional to the overburden pressure. This similarity is based on the equilibrium of the strain of the pile and the soil during ultimate stage.

In this section, we will use some important force balances for discussion about the similarity for static experiment, so a similarity for time scale will not be discussed.

Similarity during soil fractured

The similarity during soil fractured is examined in this section, although usually the initial shear modulus and the decreasing ratio of the shear modulus are considered on the small strain of the soil. The scaling factor for the ground depth is defined λ as shown in equation (1). Where, the subscripts "p" and "m" mean prototype and model respectively. In 1g gravitational field, the scaling factor for the confining pressure becomes λ inevitably. The ultimate shear strength of the soil ($\tau_{\max}$) is expressed by the effective confining pressure (σ), the internal friction (ϕ) and the cohesion(c). And the shear strength is the product of the shear modulus and the strain (equation (3)).

The internal friction at model must not be different with prototype easily. Consequently, at sandy soil, the scaling factor of the ultimate shear strength (τ_p / τ_m) is also obtained λ. On the other hand, the shear modulus of the soil is able to change at some degree by a compaction. Now, by using parameter α, the soil shear modulus is defined in equation (4). In this case, the scaling factor for the strain is derived in equation (5) inevitably. So if the soil modulus is decided independently, the scaling factor for strain is uniquely determined.

$$\lambda = {\ell_p}/{\ell_m} \qquad (1)$$

$$\tau_{max} = \sigma tan\phi \qquad (2)$$

$$\tau = G\gamma \qquad (3)$$

λ : scaling factor for pile length
ℓ_p : pile length for prototype
ℓ_m : pile length for model
$\tau_{\max}$: ultimate shear strength
σ : effective confining pressure
ϕ : internal friction of sand
τ : shear force
G : soil shear modulus
γ : strain (lateral displacement / pile length)

Where, let us define

$$G_p = \lambda^{\alpha} G_m \qquad (4)$$

$$\lambda_{\varepsilon} = {\gamma_p}/{\gamma_m} = \lambda^{1-\alpha} \qquad (5)$$

λ_{ε} : scaling factor for strain

Similarity during soil around pile fractured

The ultimate subgrade reaction acts on the pile is considered at Broms's formula (6) and so on without a cohesion and it is proportion to an effective confining pressure. Where, *Kp* is a coefficient of passive earth pressure, the scaling factor for *Kp* is 1,because the internal friction can not be varied. So, the scaling factor for the ultimate subgrade reaction is derived for equation (7). The scaling factor for strain is rewritten in equation (8) using by λ_{kh}.

$$p_y \propto K_p \times \rho g z \qquad (6)$$

p_y :ultimate subgrade reaction
ρ :soil density
g :gravitational acceleration
z :depth
K_p :coefficient of passive earth pressure
k_h :coefficient of subgrade reaction

$$\left(p_y\right)_p = \lambda\left(p_y\right)_m \qquad (7)$$

$$\lambda_\varepsilon = \frac{\gamma_p}{\gamma_m} = \frac{(k_h)_m}{(k_h)_p} = \lambda_{k_h}^{-1} \qquad (8)$$

λ_{k_h} : scaling factor for coefficient of subgrade reaction

Similarity during pile fractured

Flexural rigidity (the product of young's modulus and second moment of area) and longitudinal rigidity (the product of young's modulus and cross section area) must be similitude relationship between model and prototype. For the similarity law during pile fractured, same material and same ratio of thickness to diameter between model and prototype must be required. And also, the scaling factor for $1/\beta$ which is the pile characteristics parameter must be same scaling factor for the pile length.

If the soil shear modulus is assumed at equation (4), the relationship between the pile diameter and the coefficient of subgrade reaction is derived as shown in equation (10).

$$(EI)_p = \lambda^4 \lambda_{kh} \lambda_D (EI)_m \qquad (9)$$

E : young's modulus
I : second moment of area
λ_D : scaling factor for diameter of pile

$$\lambda_D = \lambda^{\frac{4}{3}} \lambda_{kh}^{\frac{1}{3}} \qquad (10)$$

Let us regard the scaling factor for the strain during pile fractured. Because in condition that the stress on the model pile should be same at prototype, the scaling factor for the strain is given at equation (11).

$$\lambda_\varepsilon = \lambda_{kh}^{-1/3} \lambda^{-1/3} \qquad (11)$$

Strict similarity during both pile and soil around pile fractured

In case where both pile and soil around pile are fractured, similarity conditions at equation (8) and equation (11) are required simultaneously. Necessary scaling factor for the strain is obtained from soil condition and pile condition. Equations (13) and (14) are deduced from both necessary conditions. The scaling factor for diameter of the pile is determined inevitably as equation (15).

$$\lambda_\varepsilon = \lambda_{kh}^{-1} = \lambda_{kh}^{-\frac{1}{3}} \lambda^{-\frac{1}{3}} \qquad (12)$$

$$\lambda_{kh} = \lambda^{\frac{1}{2}} \qquad (13)$$

$$\lambda_{\varepsilon} = \lambda^{-\frac{1}{2}} \qquad (14)$$

$$\lambda_{D} = \lambda^{\frac{3}{2}} \qquad (15)$$

In addition, the scaling factor for soil shear modulus is determined by relationships among the coefficient of subgrade reaction, the pile width and the soil shear modulus such as Francis's formula (16)[11] and so on. In that case, the parameter α is derived in equation (19).

Table 1 shows the scaling factors of representative parameters. Only the soil shear modulus is affected by relationship between Es/k_h and D.

$$k_h = \frac{1.3}{D}\frac{E_s}{1-\nu^2}\cdot\left(\frac{E_s D^4}{EI}\right)^{\frac{1}{12}} \qquad (16)$$

D :pile width
ν :poisson's ratio
Es :modulus of deformation

$$\lambda_{kh} = \lambda^{\frac{13}{12}\alpha}\lambda_D^{-1} \qquad (17)$$

$$\lambda^{\frac{1}{2}} = \lambda^{\frac{13}{12}\alpha}\lambda^{-\frac{3}{2}} \qquad (18)$$

$$\alpha = \frac{24}{13} \qquad (19)$$

Here, we assume the coefficient of subgrade reaction is a linear function regardless of lateral displacement. If we consider the coefficient of subgrade reaction is non-linear function related horizontal displacement, α is different with one shown in table 1. However, scaling parameters except for shear modulus are not change.

Table 1 Similarity during both pile and soil around pile fractured

Parameter			Prototype/Model	$E_S/k_h \propto D$ α = 2	$E_S/k_h \propto D^{3/4}$ α = $\frac{13}{8}$	Francis α = $\frac{24}{13}$	$E_S/k_h \propto D^{1/2}$ α = $\frac{3}{2}$	$E_S/k_h \propto D^{0}$ α = $\frac{1}{2}$
Length	pile length	λ_ℓ	λ	λ				
	diameter	λ_D	λ_D	$\lambda^{\frac{3}{2}}$				
	thickness	λ_t	λ_D	$\lambda^{\frac{3}{2}}$				
	displacement of pile	λ_d	$\lambda_\varepsilon \lambda$	$\lambda^{\frac{1}{2}}$				
	strain (disp./pile length)	λ_ε	λ_{kh}^{-1}	$\lambda^{-\frac{1}{2}}$				
	strain of pile material	λ_{ε_m}	1	1				
Force	axial force	λ_N	λ_D^2	λ^3				
	bending moment	λ_M	λ_D^3	$\lambda^{\frac{9}{2}}$				
	shear force	λ_Q	$\lambda_D^3 \lambda^{-1}$	$\lambda^{\frac{7}{2}}$				
	stress	λ_σ	1	1				
Section paformance of pile	young' modulus	λ_E	1	1				
	second moment of area	λ_I	λ_D^4	λ^6				
	flexural rigidity	λ_{EI}	λ_D^4	λ^6				
	inclined angle	λ_θ	λ_ε	$\lambda^{-\frac{1}{2}}$				
	curvature	λ_{curv}	λ_D^{-1}	$\lambda^{-\frac{3}{2}}$				
Ground characteristic	modulus of deformantion	λ_{Es}	λ^α	λ^2	$\lambda^{\frac{13}{8}}$	$\lambda^{\frac{24}{13}}$	$\lambda^{\frac{3}{2}}$	$\lambda^{\frac{1}{2}}$
	shear modulus	λ_G	$\lambda_{Es} = \lambda^\alpha$	λ^2	$\lambda^{\frac{13}{8}}$	$\lambda^{\frac{24}{13}}$	$\lambda^{\frac{3}{2}}$	$\lambda^{\frac{1}{2}}$
	coefficient of subgrade reaction	λ_{kh}	λ_ε^{-1}	$\lambda^{\frac{1}{2}}$				
	unit weight	λ_γ	1	1				
	internal friction	λ_ϕ	1	1				
	ultimate subgrade	λ_{py}	λ	λ				

APPROXIMATED SIMILARITY

There are many difficulties to conduct the model tests in strict conditions of the soil shear modulus and the pile diameter as shown in table 1. Therefore, the approximated similarities are proposed instead of the strict similarity. The approximated similarities are that the scaling factor for strain decided by the pile necessary condition differs with one by soil condition.

The approximated similarities derived as upper idea are shown in table 2. These similarities include the strict similarity shown in table 1. Figure 1 shows the relationship between the scaling factor for strain of the pile and the soil versus α, in case of Francis's formulation. Where, the scaling factor for pile length takes the value 5. In case that α is equal to 24/13, the strains of pile and soil are identical. However, both scaling factors are gradually parting according with α decrease.

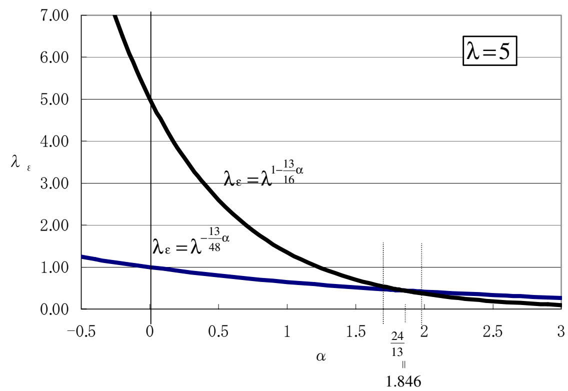

Figure 2 Relationship between scaling factor for strain and parameter α for soil shear modulus

Table 2 Approximated similarities during pile and soil around pile fractured

Parameter			Prototype/ Model	$E_S/k_h \propto D$ $\alpha\approx 2$	$E_S/k_h \propto D^{3/4}$ $\alpha\approx\frac{13}{8}$	Francis $\alpha\approx\frac{24}{13}$	$E_S/k_h \propto D^0$ $\alpha\approx\frac{1}{2}$
Length	pile length	λ_ℓ	λ	λ	λ	λ	λ
	diameter	λ_D	λ_D	$\lambda^{1+\frac{\alpha}{4}}$	$\lambda^{\frac{16}{15}}\lambda^{\frac{4\alpha}{15}}$	$\lambda\lambda^{\frac{13}{48}\alpha}$	$\lambda^{\frac{4}{3}}\lambda^{\frac{\alpha}{3}}$
	thickness	λ_t	λ_D	$\lambda^{1+\frac{\alpha}{4}}$	$\lambda^{\frac{16}{15}}\lambda^{\frac{4\alpha}{15}}$	$\lambda\lambda^{\frac{13}{48}\alpha}$	$\lambda^{\frac{4}{3}}\lambda^{\frac{\alpha}{3}}$
	displacement of pile	λ_d	$\lambda_\varepsilon\lambda$	$\lambda^{1-\frac{\alpha}{4}}$	$\lambda^{-\frac{4}{15}\alpha+\frac{14}{15}}$	$\lambda^{1-\frac{13}{48}\alpha}$	$\lambda^{-\frac{1}{3}\alpha}\lambda^{\frac{2}{3}}$
	strain of pile	λ_ε		$\lambda^{-\frac{\alpha}{4}}$	$\lambda^{-\frac{4}{15}\alpha-\frac{1}{15}}$	$\lambda^{-\frac{13}{48}\alpha}$	$\lambda^{-\frac{1}{3}\alpha}\lambda^{\frac{-1}{3}}$
	strain of ground			$\lambda^{1-\frac{3}{4}\alpha}$	$\lambda^{-\frac{4}{5}\alpha+\frac{4}{5}}$	$\lambda^{-\frac{13}{16}+1}$	$\lambda^{-\alpha}$
	strain of pile material	λ_{ε_m}	1	1	1	1	1
Force	axial force	λ_N	λ_D^2	$\lambda^{2+\frac{\alpha}{2}}$	$\lambda^{\frac{32}{15}}\lambda^{\frac{8\alpha}{15}}$	$\lambda^2\lambda^{\frac{13}{24}\alpha}$	$\lambda^{\frac{8}{3}}\lambda^{\frac{2\alpha}{3}}$
	bending moment	λ_M	λ_D^3	$\lambda^{3+\frac{3}{4}\alpha}$	$\lambda^{\frac{16}{5}}\lambda^{\frac{4\alpha}{5}}$	$\lambda^3\lambda^{\frac{13}{16}\alpha}$	$\lambda^4\lambda^\alpha$
	shear force	λ_Q	$\lambda_D^3\lambda^{-1}$	$\lambda^{2+\frac{3}{4}\alpha}$	$\lambda^{\frac{11}{5}}\lambda^{\frac{4}{5}\alpha}$	$\lambda^2\lambda^{\frac{13}{16}\alpha}$	$\lambda^3\lambda^\alpha$
	stress	λ_σ	1	1	1	1	1
Section paformance of pile	young' modulus	λ_E	1	1	1	1	1
	second moment of area	λ_I	λ_D^4	$\lambda^{4+\alpha}$	$\lambda^{\frac{64}{15}}\lambda^{\frac{16}{15}\alpha}$	$\lambda^4\lambda^{\frac{13}{12}\alpha}$	$\lambda^{\frac{16}{3}}\lambda^{\frac{4}{3}\alpha}$
	flexural rigidity	λ_{EI}	λ_D^4	$\lambda^{4+\alpha}$	$\lambda^{\frac{64}{15}}\lambda^{\frac{16}{15}\alpha}$	$\lambda^4\lambda^{\frac{13}{12}\alpha}$	$\lambda^{\frac{16}{3}}\lambda^{\frac{4}{3}\alpha}$
	inclined angle	λ_θ	λ_ε	$\lambda^{-\frac{\alpha}{4}}$	$\lambda^{-\frac{4}{15}\alpha-\frac{1}{15}}$	$\lambda^{-\frac{13}{48}\alpha}$	$\lambda^{-\frac{1}{3}\alpha}\lambda^{\frac{-1}{3}}$
	curvature	λ_{curv}	$\lambda_D^{-1}(=\lambda_\varepsilon\lambda^{-1})$	$\lambda^{-1-\frac{\alpha}{4}}$	$\lambda^{-\frac{16}{15}}\lambda^{\frac{-4}{15}\alpha}$	$\lambda^{-1}\lambda^{-\frac{13}{48}\alpha}$	$\lambda^{-\frac{4}{3}}\lambda^{-\frac{\alpha}{3}}$
Ground characteristic	modulus of deformantion	λ_{Es}	λ^α	λ^α	λ^α	λ^α	λ^α
	shear modulus	λ_G	λ^α	λ^α	λ^α	λ^α	λ^α
	coefficient of subgrade reaction	λ_{kh}	λ_ε^{-1}	$\lambda^{\frac{3}{4}\alpha-1}$	$\lambda^{\frac{4}{5}\alpha-\frac{4}{5}}$	$\lambda^{\frac{13}{16}\alpha-1}$	λ^α
	unit weight	λ_γ	1	1	1	1	1
	internal friction	λ_ϕ	1	1	1	1	1
	ultimate subgrade	λ_{py}	λ	λ	λ	λ	λ

SIMULATIONS BY BEAM-SPRING MODEL

The approximated similarities derived at former section were examined by the numerical simulation tests.

Analytical conditions

The pile length is 24m, the coefficient of subgrade reaction is $1.176\times10^{3}\,z$,(kN/m^3/m) in where z is the depth as shown in figure 2 and table 3. The reflection spring is defined by a bilinear function and the ultimate subgrade reaction (Py) is defined $3Kp\rho gz$ as shown in figure 3.

Four models case studies varied parameter α were calculated for one prototype shown in table 4. The scaling factor for pile length is 5 at all cases. The scaling factors for pile width and lateral displacement at Model-1 are also 5. In case of Model-4, the scaling factors for pile width and soil shear modulus have a strict similarity during fracture.

Table 3 Pile and soil properties of the prototype

Pile	Length	24 (m)
	Diameter	826 (mm)
	Thickness	18.5 (mm)
	Yield stress	$3.1*10^{5}$ (kN/m^3)
Groud	Internal friction	35 (degree)
	Coefficient of subgrade reaction	$1.176*10^{3}z$ (kN/m^3/m)
	Unit weight	1.57 (kN/m^3)

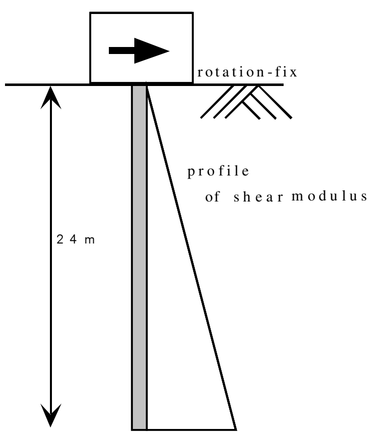

Figure 2 Cross section of the prototype pile for analysis

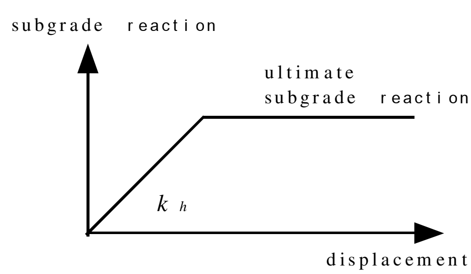

Figure 3 Subgrade reaction used for analysis

Table 4 Simulated cases (Model-1 to Model-4)

Parameter			Prototype/ Model	*p*	*m1*	*m2*	*m3*	*m4*
				Prototype	α =0	α =0.5	α =1.0	α =24/ 13
Length	pile length	λ_ℓ	λ	1	5	5	5	5
	diameter	λ_D	$\lambda\lambda^{\frac{13}{48}\alpha}$	1	5	6.22	7.73	11.18
	thickness	λ_t	$\lambda\lambda^{\frac{13}{48}\alpha}$	1	5	6.22	7.73	11.18
	displacement of pile	λ_d	$\lambda^{1-\frac{13}{48}\alpha}$	1	5	4.02	3.23	2.24
	strain of pile	λ_ε	$\lambda^{-\frac{13}{48}\alpha}$	1	1	0.80	0.65	0.45
	strain of ground		$\lambda\lambda^{-\frac{13}{16}\alpha+1}$	1	5.00	2.60	1.35	0.45
	strain of pile material	λ_{ε_m}	1	1	1	1	1	1
Force	axial force	λ_N	$\lambda^2\lambda^{\frac{13}{24}\alpha}$	1	25	38.66	59.78	125
	bending moment	λ_M	$\lambda^3\lambda^{\frac{13}{16}\alpha}$	1	125	240.36	462.19	1397.54
	shear force	λ_Q	$\lambda^2\lambda^{\frac{13}{16}\alpha}$	1	25	48.07	92.44	279.51
	stress	λ_σ	1	1	1	1	1	1
Section paformance of pile	young' modulus	λ_E	1	1	1	1	1	1
	second moment of area	λ_I	$\lambda^4\lambda^{\frac{13}{12}\alpha}$	1	625	1494.48	3573.53	15625
	flexural rigidity	λ_{EI}	$\lambda^4\lambda^{\frac{13}{12}\alpha}$	1	625	1494.48	3573.53	15625
	inclined angle	λ_θ	$\lambda^{-\frac{13}{48}\alpha}$	1	1	0.80	0.65	0.45
	curvature	λ_{curv}	$\lambda^{-1}\lambda^{-\frac{13}{48}\alpha}$	1	0.2	0.16	0.13	0.09
Ground characteristic	modulus of deformantion	λ_{Es}	λ^α	1	1	2.24	5	19.52
	shear modulus	λ_G	λ^α	1	1	2.24	5	19.52
	coefficient of subgrade reaction	λ_{kh}	$\lambda^{\frac{13}{16}\alpha-1}$	1	0.2	0.38	0.74	2.24
	unit weight	λ_γ	1	1	1	1	1	1
	internal friction	λ_ϕ	1	1	1	1	1	1
	ultimate subgrade	λ_{py}	λ	1	5	5	5	5

Simulated results

Examples of the calculated results are shown in figure 4 (lateral displacement of the pile head is 25 mm), figure 5 (175 mm) and figure 6 (350mm) respectively. These all results are converted in the prototype scale. At 25mm in figure 4, because both the soil and the pile still have not damaged, the either approximated similarities are successful to simulate to the prototype performance.

At 175mm in figure 5, the pile was damaged at head part in case of prototype. Soil near the surface was fractured in cases of Model-1, -2 and -3, so a coefficient of subgrade reaction near surface decreased. On the other hand, in cases of Model-4 and prototype, soils still have not damaged. The shear force on the pile head in Model-1 was 40 percent smaller than one of the prototype, but Model-3 could almost simulate for prototype in spite of approximated similarity.

At 350mm in figure 6, the piles were also damaged at intermediate part. All of the model cases could not simulate for prototype except for Model-4. The results of Model-4 completely agreed with prototype performance.

In these simulations, it is not considered exactly that the relationship between the soil shear modulus and strain curve was affected by confining pressure. Therefore, it is considered within the small strain level, other present similarities are better than this proposed similarity. However, proposed strict similarity is applicable for model tests in a region of the ultimate stage.

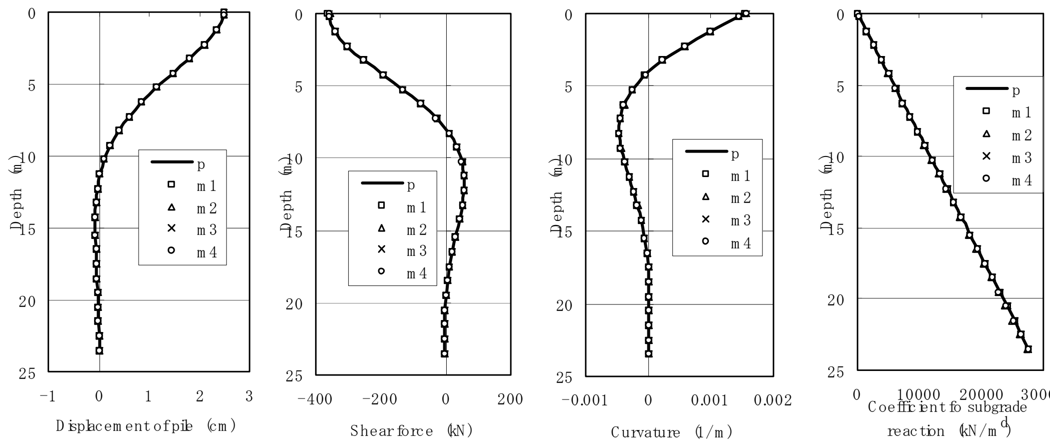

Figure 4 Distributions of the displacement, shear force, curvature and coefficient of subgrade reaction (In case of 25mm for lateral displacement of pile head)

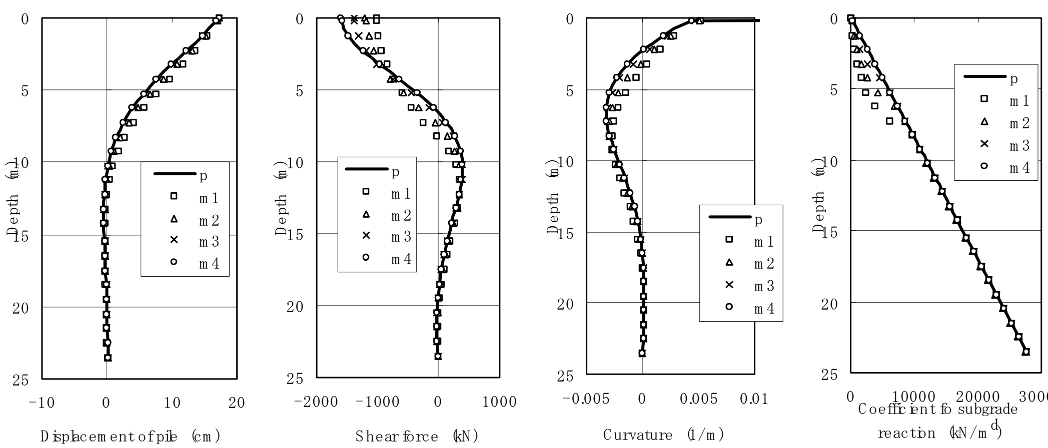

Figure 5 Distributions of the displacement, shear force, curvature and coefficient of subgrade reaction (In case of 175mm for lateral displacement of pile head)

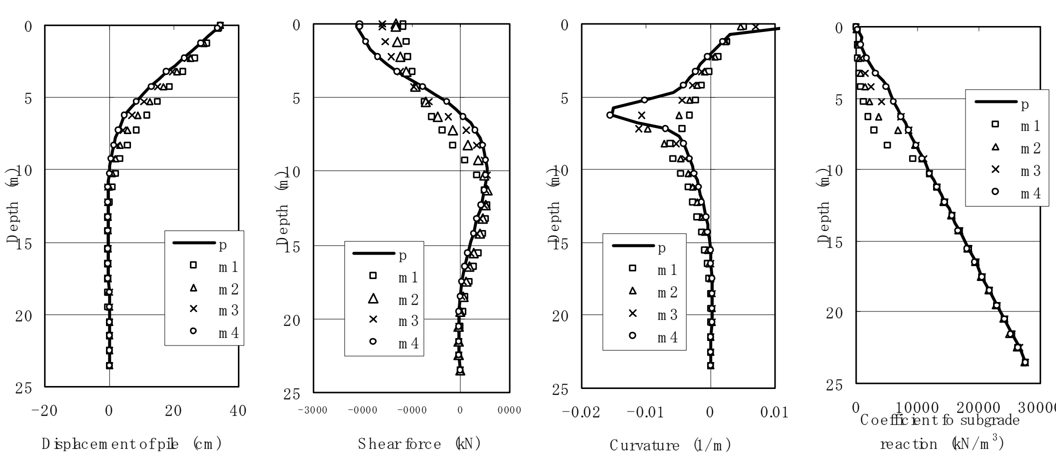

Figure 6 Distributions of the displacement, shear force, curvature and coefficient of subgrade reaction (In case of 350mm for lateral displacement of pile head)

CONCLUSIONS

The similarity conditions, which were perceived to the fracture of a pile and a soil, were proposed for large deformation tests. The approximated similarities that gave a degree of freedom to the soil shear modulus and the pile diameter are proposed instead of a strict agreement of the strain scale of the pile and soil. As the results of numerical simulations, approximated similarities are available during a little soil fractured.

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