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A simplified analysis for an earthquake resistant reinforcement of pile foundations

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ABSTRACT: The objective of this study is to develop a simplified design method for the earthquake resistant reinforcement of pile foundations with a solidification body. For the simplified design a two-layer rigid frame structure in elastic ground is selected as an analytical model. The horizontal load representing the inertia force of the upper structure due to an earthquake, is applied at the top of pile. The model of the ground is composed of several soil layers which have individual rigidities for the horizontal displacement of the pile. A transfer matrix method is applied for the simplified analysis. From the results of the series of analyses, it is clear that the simplified analysis of the earthquake resistant reinforcement of piles with a soil solidification body, developed herein, can be applied to determine the optimum shape and the optimum creation depth of a soil solidification body for the simplified design.

1 INTRODUCTION

Severe earthquake damages in the metropolitan regions of Japan is highly possible. The assurance of the resilience of infrastructures, including foundations, is an urgent task in those areas. The authors have created a new earthquake resistant reinforcement method for pile foundations, in which piles are confined in the ground with a soil solidification body. The novel method has been adopted in practice for the reinforcement of road bridges and aqueducts to reduce earthquake damage in the central areas of Japan. For the design of the developed reinforcement technique dynamic finite element analysis has been used to verify the improvement of the earthquake resistance due to the reinforcement with the soil solidification body. It is preferable to check the improvement by a simplified method in advance of the FEM analysis.

The objective of this study is to develop a simplified design method for the earthquake resistant reinforcement of pile foundations with a soil solidification body. For the simplified design method two types of analytical model are selected. One is a pile in elastic ground. The other is a two-layer rigid frame structure in elastic ground. The horizontal load which represents the inertia force of the upper structure due to an earthquake, is applied at the top of pile. The model of the ground is composed of several soil layers which have individual rigidities for the horizontal displacement of piles. A transfer matrix method based on the solution of the differential equation for a beam on an elastic body is applied for the analysis.

In the series of analyses, the results are compared with those of a full-scale test of the earthquake resistant reinforcement of piles with a soil solidification body. The effect of the earthquake resistant reinforcement is investigated for the different depth at which a soil solidification body is created and for different rigidity of the soil layers.

2 PROPOSED EARTHQUAKE RESISTANT REINFORCEMENT OF PILES

In practice earthquake resistant reinforcement methods for pile foundations are limited due to construction restrictions like the site and space. To solve these problems, the authors proposed a new type of earthquake resistant reinforcement method, applicable even for existing pile foundations. In this method, a soil solidification body is made in the ground to surround a portion of the pile group. The structure composed of a solidification body, piles, and a footing, is idealized as a two-layer rigid frame structure. The structure is effective for the earthquake reinforcement of pile foundations. The effectiveness of the method had previously been confirmed through full-scale model tests (Adachi et al, 2006) and results from 3D FEM analyses (Adachi et al, 2009).

As an example of the proposed earthquake resistant reinforcement of piles with a soil solidification body, a schematic of a full-scale model test of a pile foundation is shown in Figure 1. This newly constructed pile foundation for the test consists of four steel pipe piles, which are 406.4 mm in outer diameter, 9.5 mm in thickness and 10.0 m in length. The space between piles is 2.0 m. The pile heads were embedded and fixed in a reinforced concrete footing with a length of 0.5 m. The dimensions of the footing are 3.8 m wide, 3.8 m long and 0.6 m thick. The dimensions of the soil solidification body acting as the reinforcing body are 3.8 m wide, 3.8 m long and 2.0 m thick. The reinforcing body is installed at a depth between 3.2 m and 5.2 m. The soil solidification body is made of cement milk which is sprayed at a high pressure from a shaft inserted in the ground. The design strength of the reinforcing body is 1 MN/m^2. Subsurface soil layers of the test site are composed of loam, clay and fine sand layers.

3 ANALYSES

3.1 *Transfer matrix*

If a pile in elastic soil is subjected to a horizontal load at a top of the pile, as shown in Figure 2, the horizontal displacement of pile y at a depth x satisfies the following equation, according to the theory of bending of beams:

$$EI\frac{d^4y}{dx^4} = -k_s \cdot D_p \cdot y = -ky \tag{1}$$

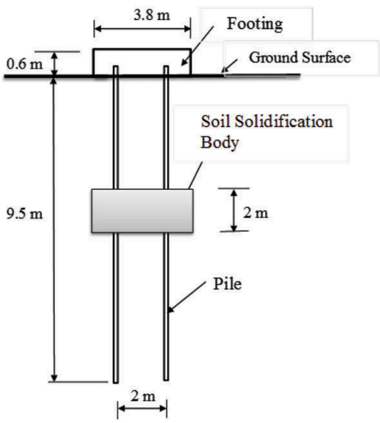

Figure 1. Schematic of the full-scale model

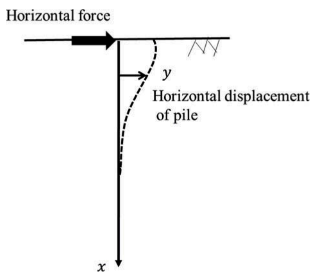

Figure 2. Displacement of a pile in elastic soil

where EI and D_p are the bending rigidity and diameter of the pile, respectively and k_s is the horizontal reaction coefficient of the soil.

Using the solution of the above differential equation for given boundary conditions in which the rotation at the top of the pile is fixed and the horizontal displacement at the bottom of the pile is zero, the relation between the values at depth x and the top of pile $(x = 0)$ are expressed by the equation:

$$\begin{pmatrix} y_j \\ \theta_j \\ M_j \\ Q_j \end{pmatrix} = \left[D_{ij}\right] \begin{pmatrix} y_0 \\ \theta_0 \\ M_0 \\ Q_0 \end{pmatrix} \tag{2}$$

where y_0, θ_0, M_0 and Q_0 are the horizontal displacement, deflection angle, bending moment, and shear force, respectively, at the top of the pile and y_j , θ_j, M_j and Q_j are the horizontal displacement, deflection angle, bending moment, and shear force, respectively, at depth x. D_{ij} is expressed as follows:

$$\begin{aligned}
D_{11} &= D_{22} = D_{33} = D_{44} = cos\beta x \cdot cosh\beta x \\
D_{12} &= -D_{34} = (cosh\beta x \cdot sin\beta x + sinh\beta x \cdot cos\beta x)/2\beta \\
D_{13} &= -D_{24} = -sinh\beta x \cdot sin\beta x/2EI\beta^3 \\
D_{14} &= (cosh\beta x \cdot sin\beta x - sinh\beta x \cdot cos\beta x)/4\beta^3 EI \\
D_{21} &= -D_{43} = \beta(sinh\beta x \cdot cos\beta x - cosh\beta x \cdot sin\beta x \\
D_{23} &= -(cosh\beta x \cdot sin\beta x + sinh\beta x \cdot cos\beta x)/2\beta EI \\
D_{31} &= -D_{42} = 2\beta^2 EIsinh\beta x \cdot sin\beta x) \\
D_{32} &= \beta EI(cos\beta x \cdot sin\beta x - sinh\beta x \cdot cos\beta x) \\
D_{41} &= -2\beta^3 EI(cosh\beta x \cdot sin\beta x + sinh\beta x \cdot cos\beta x)
\end{aligned} \tag{3}$$

where

$$\beta = \sqrt[4]{\frac{k_s \cdot D_p}{4EI}} = \sqrt[4]{\frac{k}{4EI}} \tag{4}$$

$\left[D_{ij}\right]$ is called the transfer matrix and is used for the analysis of the simplified design.

3.2 *Single pile model analysis*

It is assumed that each pile of the group of piles deforms in a similar manner as the other piles; therefore, a single pile represents a group of piles. For a single pile installed in multilayer soil, the horizontal displacement and the moment at the top of pile are estimated using

Table 1. Parameters of the subsurface soil layer for the analysis

No	Depth of bottom of the layer(m)	Thickness (m)	Coefficient of horizontal soil reaction (kN/m^3)
1	1.9	1.9	10437
2	3.2	1.3	7828
3	6.9	3.7	3080
4	8.35	1.45	20281
5	9.5	1.15	121770

transfer matrices for multilayer soil and boundary conditions. In this model, the bending stiffness of the single pile is increased at a depth where the pile is reinforced with a solidification body by considering the bending stiffness of the solidification body.

For the analysis of the full-scale model test, the following parameters are used. The bending stiffness of the pile and the solidification body are $4.41x10^4$ ($kN \cdot m^2$) and $2.27x10^7$ ($kN \cdot m^2$) respectively. One fourth of the bending stiffness of the solidification body is added to the bending stiffness of the pile at the depth where the solidification is located. The subsurface soil layers are idealized as five layers as shown in Table 1. The coefficient of horizontal soil reaction of each layer which is estimated from standard penetration test results, is shown in Table 1. The applied horizontal force at the top of the single pile is 150 kN, which is one fourth of the applied load in the full-scale test. The value of the load is estimated assuming that the maximum horizontal acceleration of the super structure is 250 cm/sec^2. The boundary conditions are as follows: the deflection angle at the top of the pile is zero and the horizontal displacement at the bottom of the pile is zero.

3.3 *Two layer rigid frame structure model analysis*

Two piles, a footing, and a solidification body, are idealized as a two-layer rigid frame structure in elastic multilayer soil, as shown in Figure 3. Individual transfer matrices relating the values at the ends of the member including the piles, a footing and a solidification body, are calculated first.

Using the transfer matrices and boundary conditions, the horizontal displacement and bending moment at the top of piles are obtained assuming there is a parallel deformation of the two piles. The dimensions of the two-layer rigid frame structure model used for the analysis of the full-scale model test are shown in Figure 3. The bending stiffness of the footing is $2.67x10^7$ ($kN \cdot m^2$) Other parameters and boundary conditions are the same as those used for the single pile model analysis.

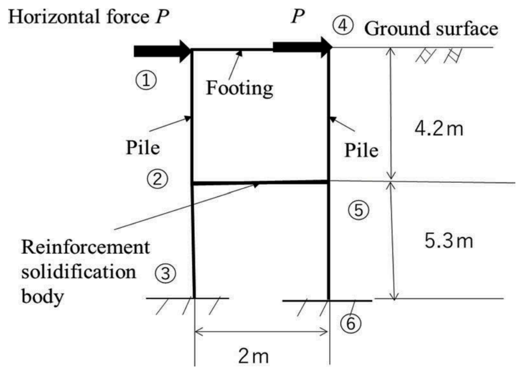

Figure 3. Two-layer rigid frame structure model

4 RESULTS

Results of the analyses and the full-scale model test are compared in Figures 4 and 5. Figure 4 shows the horizontal displacement of the pile subjected to the horizontal load at

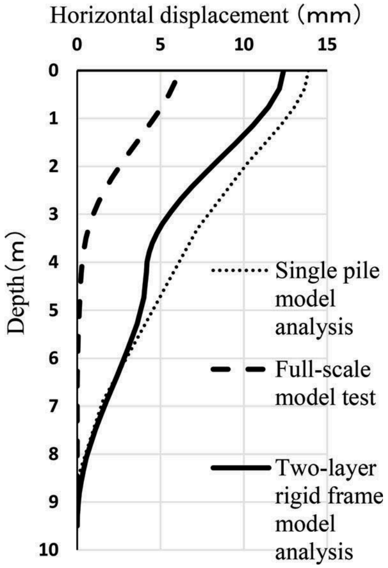

Figure 4. Comparison of the horizontal displacement between the analyses and the full-scaled test

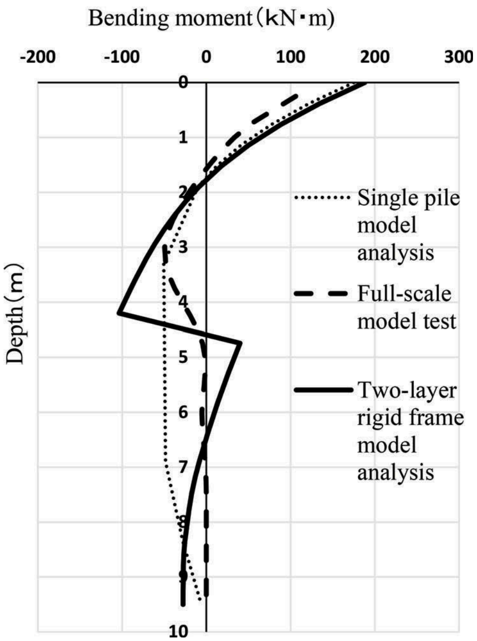

Figure 5. Comparison of the bending moment between the analyses and the full-scaled test

the top of pile. The horizontal displacement of the pile, based on the analysis of the two-layer rigid frame structure model, decreases significantly below a depth of 3.2 m, where the upper surface of the reinforcement with the solidification body is located. This shape of distribution of the pile displacement based on a two-layer rigid frame structure model is more similar to the full-scale test than the distribution from the single pile model. It is considered that the analysis of two-layer rigid frame structure model is more suited to understand the characteristics of the displacement of the reinforced pile than the analysis of the single pile model. The displacement at the top of pile, which is the maximum, obtained by the analyses using a single pile model and the two-layer rigid frame structure model are larger than the displacement from the full-scale test. The loading test of the reinforced pile with the solidification body was performed after the loading test of the pile without reinforcement. It is presumed that the maximum displacement of the reinforced pile became smaller because of the over consolidation effect of soil that was introduced due to the preceding loading test for the unreinforced pile.

Figure 5 shows the bending moment of the pile induced by the horizontal loading. The bending moment induced due to the lateral loading in the full-scale test decreases significantly below the solidification body. The distribution of the bending moment of the pile based on the analysis of the two-layer rigid frame structure model is more similar to the results from the full-scale test than the ones from the single pile model analysis. It is considered that the two-layer rigid frame structure model analysis is better than the single pile model analysis for identifying the characteristics of the bending moment of the reinforced pile subject to a horizontal force. The bending moment at the top of pile which is the maximum value, obtained by the analyses using a single pile model and the two-layer rigid frame structure model are larger than the bending moment from the full-scale test. The difference in the bending moment is presumed to be caused by the difference in the displacement due to the over consolidation effect of soil mentioned previously.

5 SIMPLIFIED DESIGN METHOD

Figure 6 shows the relation between the depth of the upper surface of the solidification body and the effect of the earthquake resistance due to the reinforcement with the solidification body, calculated using the two-layer rigid frame structure model analysis for the full-scaled test model. The ratio of the calculated maximum value for the reinforced pile to the value obtained for the unreinforced pile is considered to express the effect of the reinforcement. The vertical axis in Figure 6 denotes the ratio of the reinforcement effect. If the dimensions and the material properties of the pile, footing, and solidification body are given, the depth where the solidification body should be constructed, can be determined for a required reduction of the maximum bending moment and maximum horizontal displacement of a pile for a specified earthquake force. This figure is applicable for the simplified design of the earthquake reinforcement of a pile with a solidification body using the two-layer rigid frame structure model analysis.

To compare the results of the reinforcement effect with the simplified method three- dimension dynamic FEM analyses were performed. 10.4 m thick, 100 m long and 20 m wide ground was used in the FEM analyses. A half section of 40 m wide ground was considered, assuming symmetrical deformation. The side boundary displacements are free in the horizontal direction and fixed in the vertical direction assuming shear deformation. The bottom displacements are fixed in both the horizontal and vertical directions. Beam elements are used for the pile. It is assumed that the displacement of the pile is the same as the displacement of the adjacent soil at the same depth.

The nonlinear dynamic behavior of the soils is calculated using the Modified Ramberg Osgood model. The parameters of the soils such as G_0 and h_{max} are determined by referring to the results of cyclic shear tests. The specified earthquake wave for the design of road bridges in Japan was used as the input motion for the FEM analyses. The values of the input motion

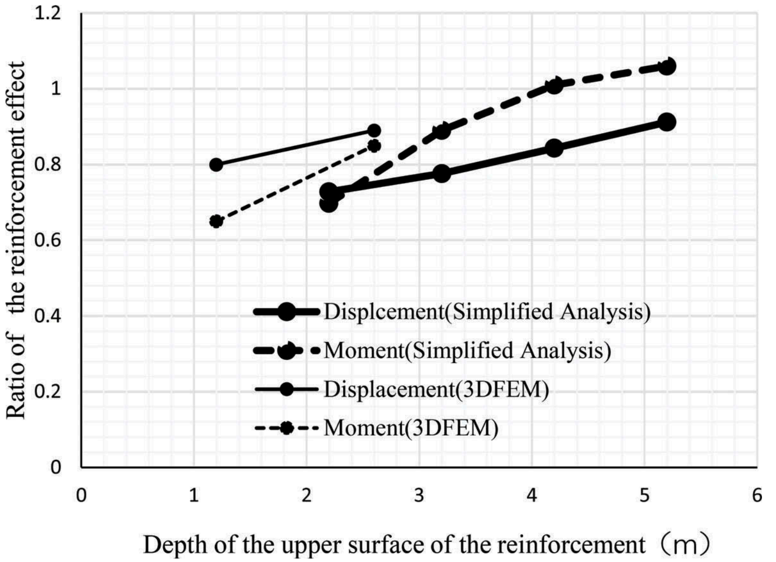

Figure 6. Relation between the effect of the reinforcement and the depth of the reinforcement

were adjusted to satisfy the condition that the maximum horizontal acceleration at the surface of the ground is about 250 m/s^2.

The dynamic FEM analyses were performed for the cases where the depth of the upper surface of the reinforcement body are 1.2 m and 2.55 m and for the case where the reinforcement body does not exist in the ground. For the three cases the maximum horizontal displacement and maximum bending moment of the pile were compared; the effects of the reinforcement were calculated, as shown in Figure 6. The effect of the reinforcement based on the 3D dynamic FEM analysis are larger than the values from the simplified analysis. The tendency that the ratio of the reinforcement effect becomes smaller due to the decrease of the depth of the reinforcement, is the same for the two types of analyses. It is considered that the simplified analysis is applicable for the preliminary design in advance of the dynamic FEM analysis.

6 CONCLUSIONS

Based on the results the followings are made clear:

1. A reduction of the maximum bending moment and the maximum horizontal displacement of the piles, that is the effect induced by an earthquake resistant reinforcement, can be resolved using an analysis with a two-layer rigid frame structure model.
2. To apply the simplified design of an earthquake resistant pile reinforcement with a soil solidification body, a transfer matrix analysis of a two-layer rigid frame structure model can be used to determine the optimum shape and depth of a soil solidification body for different types of piles and soil layers.

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