Static Pile Head Impedance using 3D Nonlinear FEM Analysis

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ABSTRACT

This paper focuses on the local nonlinearlity associated with inelasticity of soil around a pile foundation. To consider the 3D nonlinearlity of soil, the 2nd invariant of stress and strain deviators are introduced and the nonlinear relation between those two invariants are assumed to follow R- O model. Before proceeding to dynamic soil - pile interaction problem, a static lateral force - displacement relation ship at a single pile head is studied. In the first step, the combined effects of normal and shear stress of soil around a pile is evaluated by 2D FEM analysis. In the second step, 3D FEM analyses are conducted and compared with the results of 2D FEM analyses. Then, the effect of a pile volume and the appropriate thickness of plane strain elements for 2D FEM analysis are discussed.

Keywords: Static pile head impedance, Nonlinear soil-pile interaction, 3D FEM analysis, R-O model, 2nd invariant of strain deviator

INTRODUCTION

As is well known, nonlinear soil structure interaction effects may be classified into two kind of nonlinearlities; the one is the site nonlinearlity or the primary nonlinearlity associated with inelastic behavior of soils subjected to strong earthquake motion, and the other is the local nonlinearlity or the secondly nonlinearlity resulting from inelasticity of soil or loss of contact between the foundation and the surrounding soil.

This paper focuses on the local nonlinearlity associated with inelasticity of soil around a pile foundation. Nonlinearlity of soil is modeled based on a modified R- O model [Shawky 1994] that considers the combined effects of normal and shear stress. In the first step, a static lateral force - displacement relation ship at a single pile head is studied by 2D FEM analysis and the combined effects of normal and shear stress of soil around a pile is evaluated. In the second step, 3D FEM analyses are conducted and compared with the results of 2D FEM analyses. Then, the appropriate thickness of plane strain elements for 2D FEM analysis is also discussed.

CONSTITUTIVE MODEL

To consider the 3D nonlinearlity of soil, the 2nd invariant of stress and strain deviators are introduced and the following Ohsaki's formula [Ohsaki 1982] for envelope to express the nonlinear relation between those two invariants are adopted.

$$\frac{J_2'}{M} = \frac{J_2}{2\,G_0\,M}\left(1 + \alpha\left|\frac{J_2}{S_u\,M}\right|^{\beta}\right) \qquad (1)$$

where

J'_2 = 2nd invariant of strain deviator, J_2 = 2nd invariant of stress deviator

M = hysteric coefficient for Masing law: 1.0 for loading path, 2.0 for unloading and reloading path

G_0 = initial elastic shear stiffness

$= \frac{\rho}{g} V_s^2$: where ρ = unit weight of soil, V_s = shear wave velocity, g = gravity acceleration

α = parameter depending on failure strain

β = parameter concerning hysteretic damping

$= \frac{2 \pi h_{max}}{2 - \pi h_{max}}$: where h_{max} is maximum hysteretic damping

This idea of analyses are originally proposed by Shawky [Shawky 1994] and several applications to soil-structure interaction analyses have started recently [Fukushima *et al*. 1999, Sakashita *et al*. 1999]. The practical significance of this method is its applicability to several kind of 1D shear strain and stress relationships such as R-O or H-D models which were proposed based on experimental data. The applicability of 1D constitutive model to evaluate 3D nonlineality has been recently investigated through experimental study on the behavior of soil under reversed cyclic loads [Shida *et al.* 1999].
This constitutive model is called MRO (modified R-O) model in the following analyses.

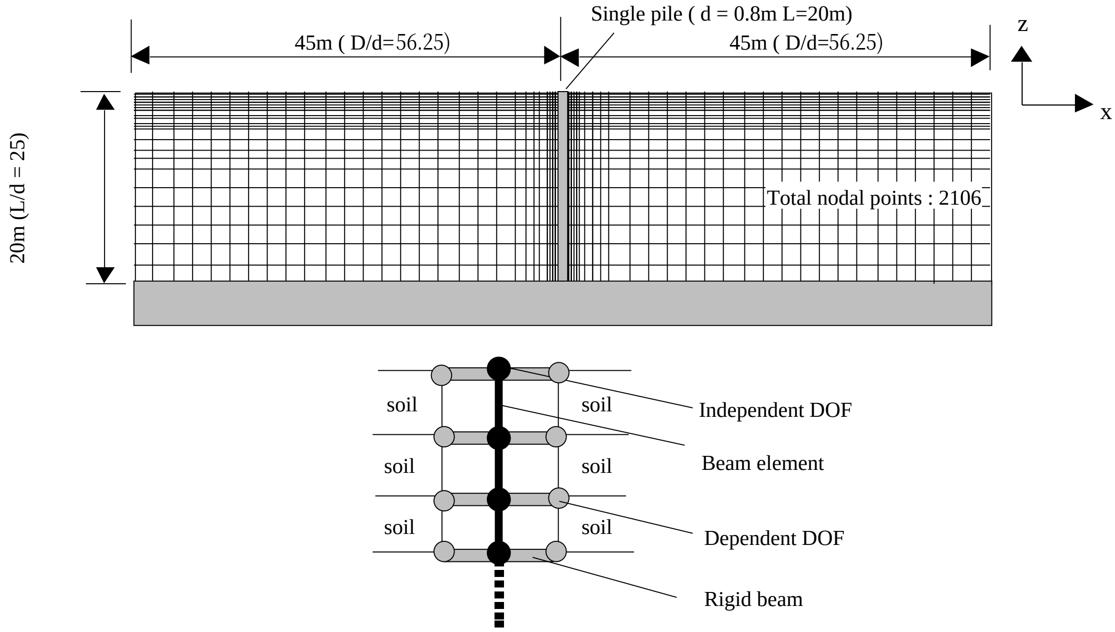
SINGLE PILE-SOIL INTERACTION ANALYSIS

Before proceeding to dynamic response analysis, fundamental study was conducted in this paper for investigating static interaction between a single pile and soil. Lateral force is applied at a pile head and the force - displacement relationship is evaluated.

2D FEM ANALYSIS

In the first step, the combined effects of normal and shear stress of soil around a pile is studied by 2D FEM analysis. The one analysis is conducted with MRO model. The other analysis is performed with ordinary RO model that considers the nonlinear relationship between shear stress and strain only, neglecting the effect of normal stress. The finite element mesh for the analysis is shown in Figure1. The properties of uniform sandy soil and the profiles of a steel pile are listed in Table 1 and 2, respectively. As shown in Figure 2., the parameters of MRO model are determined such that maximum hysteretic damping is 25% and the initial elastic shear stiffness decreased to 50% at 4.0×10^{-4} strain. The soil and pile are fixed at the base. The thickness of plane strain elements for soil is assumed as 3.75m (= 4.69 d), accounting for the results of 3D FEM analysis presented afterward. To consider the volume of pile, additional nodes are defined around the pile nodes and they are connected each other with rigid beams, as shown in Figure 1. The pile head rotation is constrained and the lateral force is applied at the pile head, increasing to 980 kN.

Figure 3 shows the lateral force - displacement relationship with MRO model. The solid and dotted lines show the results with two side boundary conditions of fixed and free, respectively. There is a little difference between two results, which indicates the modelling error of infinite extent in horizontal direction.



Detail of a single pile model considering its volume

Figure.1 2D **FEM model for a single pile - soil interaction analysis.**

Table 1. **Soil properties**

Shear wave velocity	100 m/sec.
Poissons ratio	0.48
Bulk unit weight	15.7 kN / m^3
Thickness	20 m

Table 2 **Profiles of steel pile.**

Diameter	0.8 m
Length	20 m
Thickness	0.016 m
E	2.06×10^8 kN / m^2
I	2.67×10^{-3} m^4

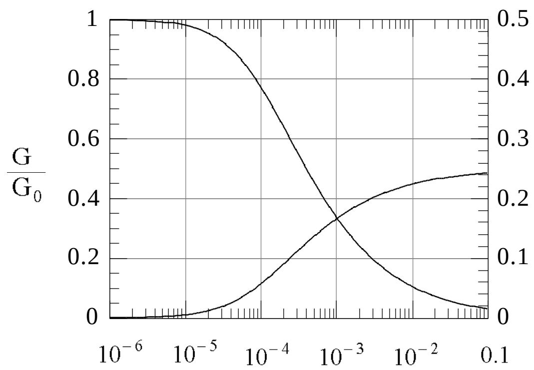


Figure 2 Strain dependency of stiffness and damping expressed by MRO model.

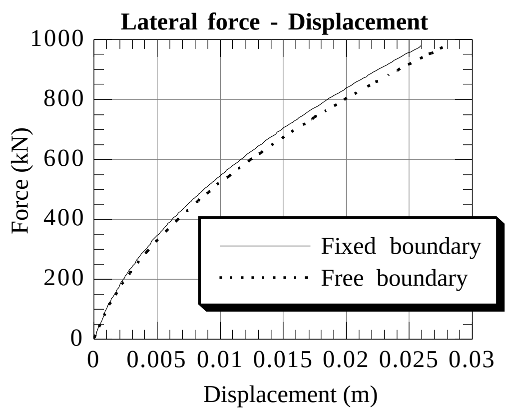


Figure 3. Lateral force - displacement relationship with MRO model

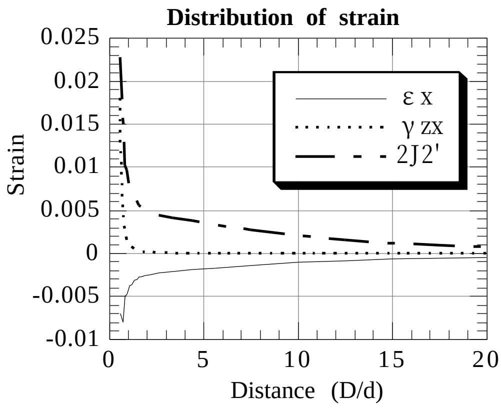


Figure 4. distribution of maximum strain along soil surface at GL-10cm.

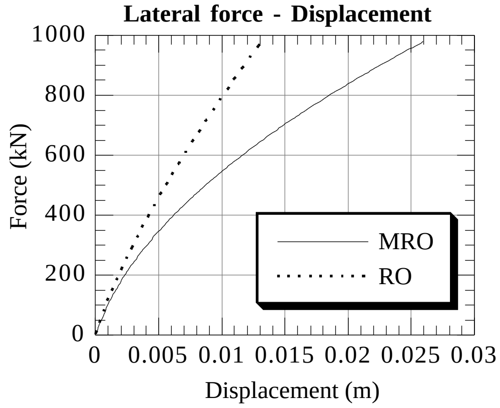
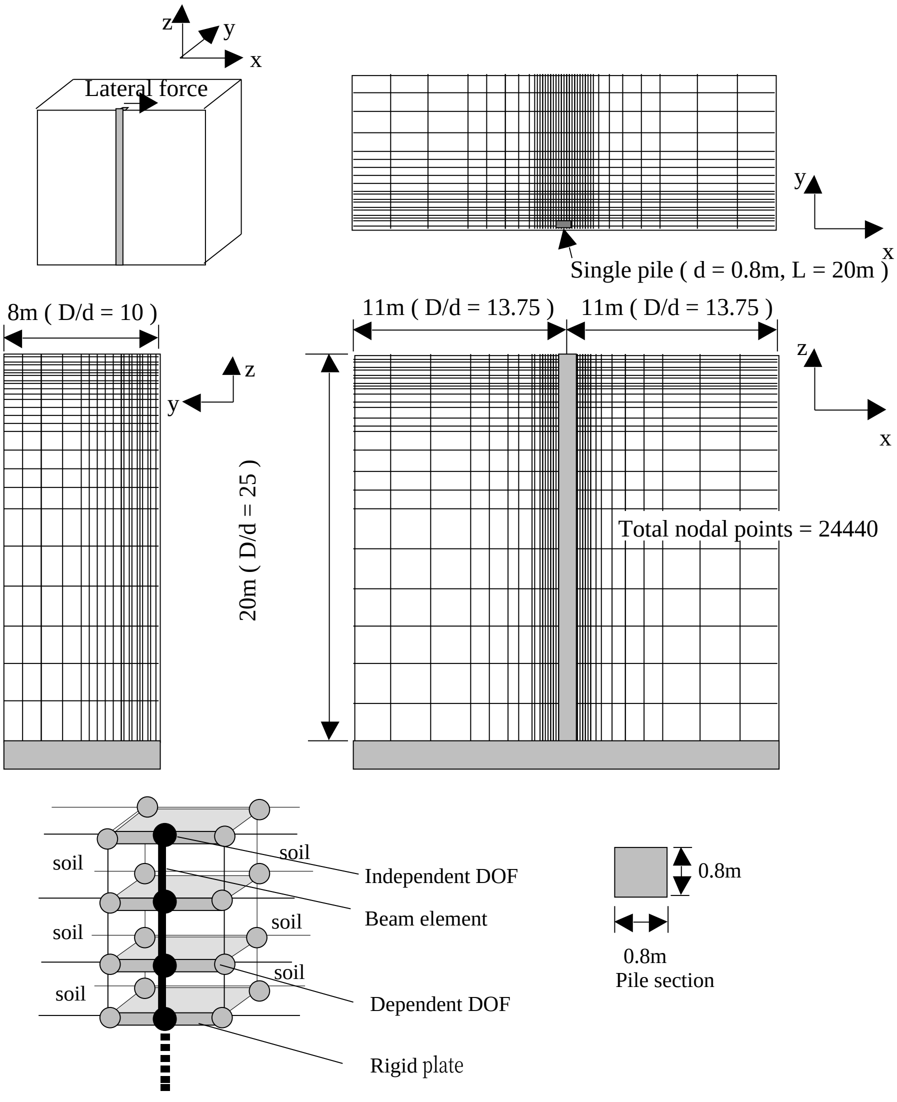


Figure 5. Comparison of lateral force - displacement relationship with MRO and RO model.



Detail of a single pile model considering its volume

Figure 6 3D FEM model for a single pile - soil interaction analysis

Figure 4 shows the distribution of the maximum values of the shear strain γ_{xz}, normal strain ε_x, and $2J_2'$ along the soil surface at GL-10cm. The value of $2J_2'$ can be regarded as generalized shear strain that indicates strain intensity of soil, because it coincides with shear strain γ_{xz} without normal stress. The large shear strain or strong nonlinearlity of soil is concentrated around the pile. This area of nonlinearlity seems to expand by considering the effect of normal strain of soil.

Figure 5 shows the comparison of the results obtained by MRO model and RO model. This figure indicates the normal stress has unnegligible effects on the static pile head impedance.

3D FEM ANALYSIS

In the second step, the combined effects of normal and shear stress of soil around a pile is studied by 3D FEM analysis. The lateral force - displacement relationship obtained by the analysis is compared with the results of 2D FEM analysis, to evaluate an appropriate thickness of plane elements for 2D FEM analysis. The effects of pile volume is also studied.

The finite element mesh for the analysis is shown in Figure 6. To take the symmetry of the model into account, 1/2 size of the total model is considered. The properties of uniform sandy soil and the profiles of a steel pile are the same as those used for 2D FEM analysis. The lateral width of finite element mesh may be expected to be reduced compared with 2D FEM analysis, because the reaction force to the pile is supplied from transverse direction besides lateral and vertical directions. For this reason as well as for saving the computational load, the lateral width of the model is reduced to 22 m (D/d = 27.5). To consider the pile volume, additional nodes are defined around the pile nodes and they are connected each other with rigid plates, as shown in Figure 6. Here, the pile section is assumed to have square shape of $0.8\text{m} \times 0.8\text{m}$ to simplify the analysis.

Figure 7 shows the lateral force - displacement relationship. The solid and dotted lines show the results with two side boundary conditions of fixed and free, respectively. There is not a little difference between the two results, which indicates the modelling error of finite extent in lateral and transverse directions. The proper result free from the error is expected to lie between those two lines. The strain distributions at GL-10cm, calculated with fixed side boundary condition are shown in Figure 8. The generalized shear strain $2J_2'$ rapidly decreases along x1 axis, as it is observed in 2D FEM analysis. The maximum value beneath the pile doubled compared with the 2D FEM results but it decreases rapidly along y1 axis in transverse direction. The shear strain γ_{xy}, on the other hand dominates along y2 axis.

Figure 8 shows the effects of the pile volume to the lateral force - displacement relationship. This figure indicates that the static pile head impedance may be underestimated if the pile volume is neglected. However, it should be noted that the results of 3D FEM analyses does not necessarily presents the actual impedance because the loss of contact at the pile interface is not considered in this study. Comparison with experimental data will be necessary in the next step.

To estimate an appropriate thickness of plane strain elements for 2D FEM analysis, the lateral force - displacement relationship obtained by 3D FEM analysis is compared with the results of 2D FEM analysis for the different thickness of 2D finite element ranging between 3.0m and 4.5m, i.e. 3.0, 3.5, 4.0, 4.5m. Figure 9 shows the comparison

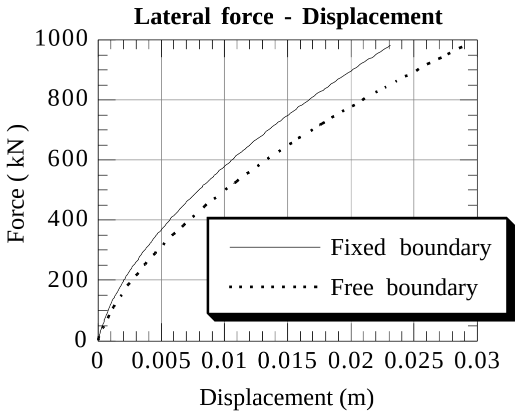


Figure 7 Lateral force - displacement relationship with 3D FEM analysis

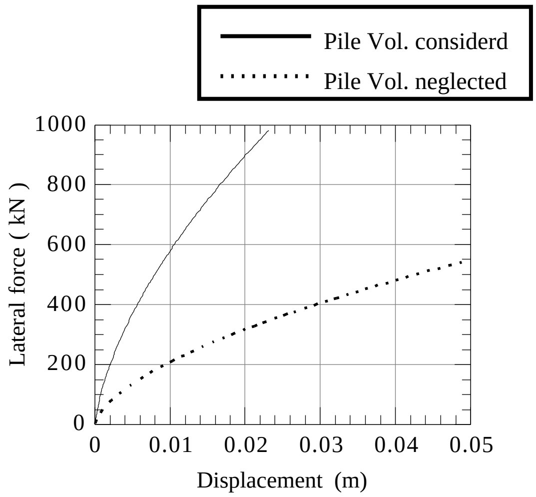
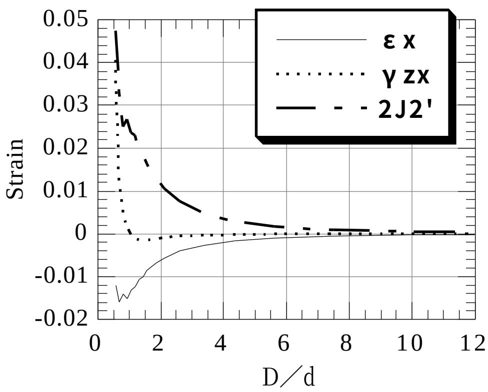
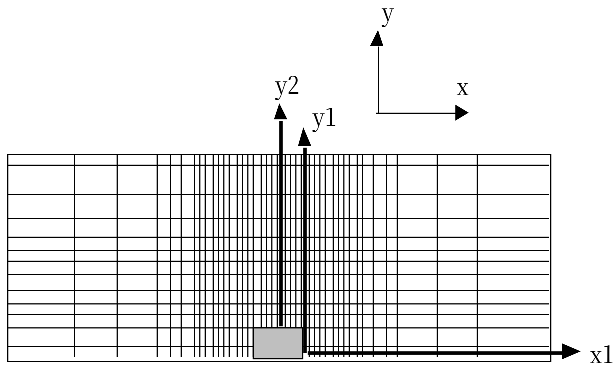
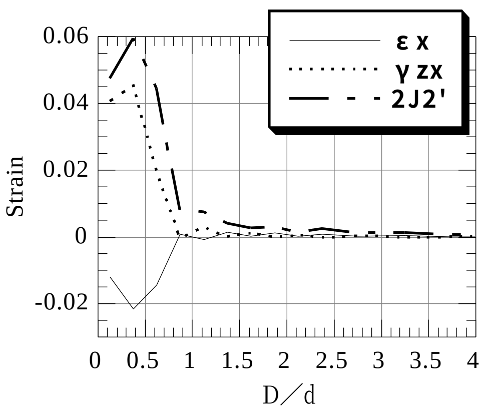


Figure 9 Lateral force - displacement relationship with and without pile volume considered.

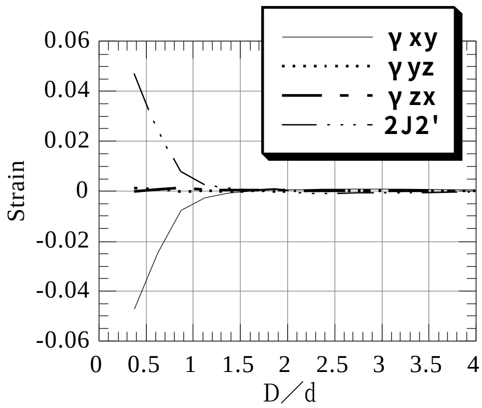


(a) Maximum strain along x1





(b) Maximum strain along y1



(c) Maximum strain along y2

Figure 8 Maximum strain distribution at GL-10cm

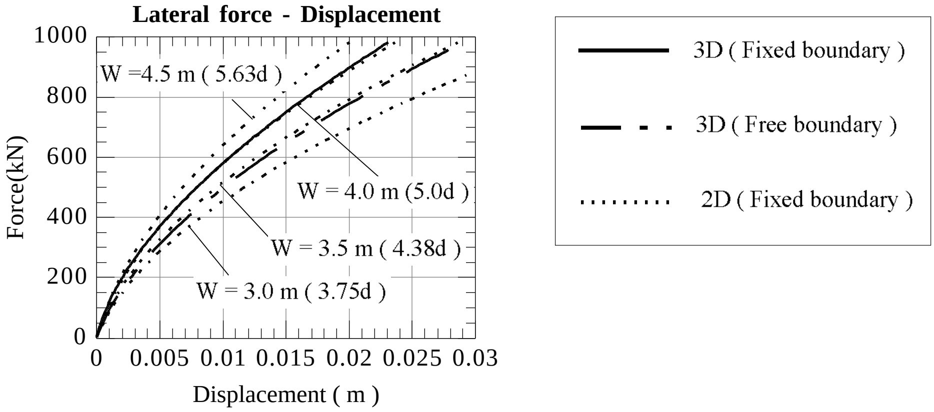


Figure 9 Comparison of 2D and 3D FEM analysis.

of the results obtained by 3D and 2D FEM analysis. The results of 3D FEM analysis with fixed and free side boundary conditions have good agreement with those of 2D FEM analysis with thickness w = 4.0m and 3.5m, respectively. The appropriate thickness seem to lie somewhere between 3.5m and 4.0m. For this reason, w = 3.75m is adopted in the preceding 2D FEM analysis.

CONCLUDING REMARKS

This paper focuses on the local nonlinearlity associated with inelasticity of soil around a pile foundation. To consider the 3D nonlinearlity of soil, the 2nd invariant of stress and strain deviators are introduced and the nonlinear relation between those two invariants are assumed to follow R- O model. Before proceeding to dynamic soil - pile interaction problem, a static lateral force - displacement relation ship at a single pile head is studied by 2D and 3D FEM analysis. Through the results of the numerical study, the following concluding remarks are obtained.
1) The normal strain at the pile interface has unnegligible effects on the static pile head impedance. The normal strain seems to expand the area of nonlinearlity along lateral forcing direction of a pile.
2) The static pile head impedance may be underestimated if the pile volume is neglected. However, it should be noted that the results of 3D FEM analyses does not necessarily present the actual impedance because the loss of contact at the pile interface is not considered in this study.
3) There exists an appropriate thickness of plane strain elements for 2D FEM analysis to approximate the static pile head impedance obtained by 3D FEM analysis.

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REFERENCES

1) Fukushima K., Okamoto S., Sakashita K., Tateishi A., Shida T., "Proposal of constitutive model of soil applicable to dynamic soil-structure interaction analyses under large strain."Proceeding of the 25th JSCE Earthquake

Engineering Symposium, Vol.1, pp.449 - 452,1999.7. (in Japanese)

2) Ohsaki Y. Dynamic nonlinear model and one-dimensional nonlinear response of soil deposits, (Research report 82-02), Dept. of Architecture, Tokyo Univ., 1982.3.

3) Sakashita K., Okamoto S., Fukushima K., Shida T., Tateishi A., "Dynamic nonlinear response analysis of sandy soil under strong earthquake motion", Proceeding of the 25th JSCE Earthquake Engineering Symposium, Vol.1, pp.301 - 304, 1999.7. (in Japanese)

4) Shawky A. A., Nonlinear static and dynamic analysis for underground reinforced concrete. *Dr. Engineering Thesis*, Department of Civil Engineering, University of Tokyo, 1994.

5) Shida T., Fukushima K., Tateishi A., Kuwano J., Hashimoto S., "Nonlinear behavior of sand subjected to various combinations of stress pass under reversed cyclic load. "Proceedings of the 54th Annual Conference of the JSCE, 3-A, pp.166 - 167, 1999.9. (in Japanese)