Research on Streamlining Seismic Safety Evaluation of Underground Reinforced Concrete Duct-Type Structures in Nuclear Power Stations

-Part-4. Analytical Simulation by Sophisticated RC Micro-model and Simple Soil Model–

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ABSTRACT

The present paper deals with numerical analysis correlation with plastic deformation of scaled RC structures under dynamic soil-structure interaction. An elaborated nonlinear FEM analysis that incorporates with RC constitutive laws and hysteretic dependent soil stress-strain relation is concerned for this purpose. The accuracy of the numerical analysis result is discussed on ground response, structure deformation and soil-structure interaction. Relatively good correlation is observed in ground response and structure deformation as a result of appropriate soil nonlinear modeling. Fair estimation is also identified for soil structure interaction. Throughout the correlation work, the accuracy of the numerical analysis is found to be acceptable for engineering practice purposes.

INTRODUCTION

Earthquake resistance of underground RC structures has been one of the major research topics among earthquake engineering circles in Japan. On the contrary to so-called above ground structures, underground structures suffer from not only inertia force but also soil-structure interaction effect during an earthquake. In other words, their seismic performance is strongly affected by ground deformation. This yields somewhat complicated manner for estimating seismic force on these structures. Besides the collapse of several subways stations prompted us to study in deep and develop earthquake resistant design of underground RC structures.

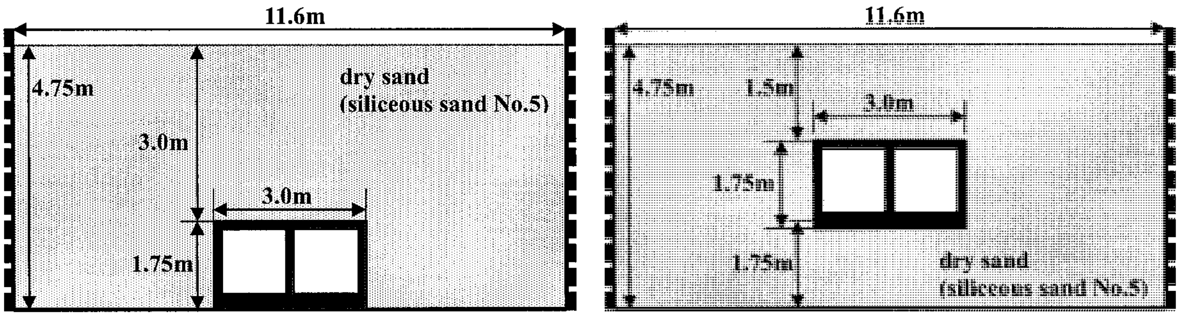
Nonlinear FEM analysis is believed to be a powerful tool for assessing seismic performance and possible damage development especially during an extremely strong ground shaking. Two types of nonlinear FEM analyses are currently used in academic and engineering practice communities. The one is rather conventional version in which moment-curvature relation is used to represent RC member deformation. The other is more sophisticated one in which straightforward RC constitutive models for concrete and reinforcement are employed. To corroborate such a tool, numerical correlations have been conducted with regards to experimental data and case histories from past earthquake damages. Shawky [1] demonstrated the accuracy of the computer program WCOMD that incorporates with soil nonlinear model for plastic deformation of scaled RC box structures under static soil-structure interaction testing. AN [2] also examined the failure mechanism of a subway station occurred during the 1995 Great Kobe Earthquake using the similar program. The analysis well explained that the shear failure of center column triggered the structure collapse during the earthquake. However, more efforts to validate such analysis tools are needed, particularly in damage development evaluation, i.e. reinforcement yielding, concrete crack opening and the degree of plastic deformation under cyclic reversed soil-structure interaction.

As is presented in previous studies [3,4], one of the authors identified some unique aspects of plastic deformation of the model RC structures based on larger size shake table test. Then the primary object of the present paper is to validate nonlinear FEM analysis that employs RC constitutive models. Numerical analysis is correlated with nonlinear ground response, plastic deformation of the model RC structure and dynamic soil-structure interaction. To examine and discuss the accuracy of the RC constitutive models, emphasis is placed on yielding process and concrete crack development on the model RC structures.

ANALYSES

Shake Table Test

Two cases of test were performed in a laminar shear box using a large shaking table. The arrangement of the RC structure models in the laminar box is depicted in **Fig. 1**. One was the Fixed case, in which a two-box type RC model was fixed to the base plate of the shaking table. The other was the Unfixed case, in which the identical RC model was embedded, in the central portion of the laminar box. As far as the details of experimental procedure and results are concerned, they are presented in the related paper [4].



(a) Fixed case (b) Unfixed case

Fig. 1 Arrangement of RC boxes in the Laminar shear box

Nonlinear Models for RC and Soil

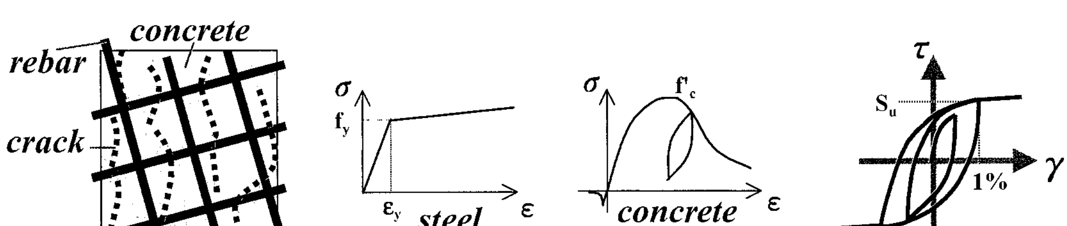
In the present paper, we applied Method B defined in the related study [3]. The basic concept of the analytical model is illustrated in **Fig. 2**. The smeared crack model [5] developed by Okamura and Maekawa (WCOMD-SJ ver.7.1) considering RC material nonlinearity was used for structure and a total stress and strain hysteresis-dependent model (modified version of Ohsaki's model) was adopted for soil nonlinearity.

The smeared crack model is used for representing cracked concrete with the fixed multidirectional cracks and all the stress-strain relationships are described as spatial average stress and average strain of concrete defined in finite elements. The RC model is constructed by combining the constitutive law for concrete and reinforcing bar. The constitutive law adopted for the cracked concrete consists of tension stiffening, the compression and shear transfer models.

A path-dependent constitutive model for soil is indispensable for dealing with kinematic interaction of RC-soil entire system under strong seismic loads. Ohsaki's model is defined in **Eq. (1)** for envelope to express the nonlinear relation of the shear-stress-strain for soil as well as internal loop with Masing's rule.

$$\gamma = \frac{\tau}{G_0}\left(1 + a\left(\frac{\tau}{S_u}\right)^b\right) \qquad a = \frac{G_0}{S_u} \times 0.01 - 1.0 \tag{1}$$

Where τ, γ are shear strain and stress, respectively. S_u is maximum shear strength of soil (defined as shear strain at γ=1%), Go is initial shear modulus of soil, b is soil type factor (1.6 for sandy soil, 1.4 for clay soil)



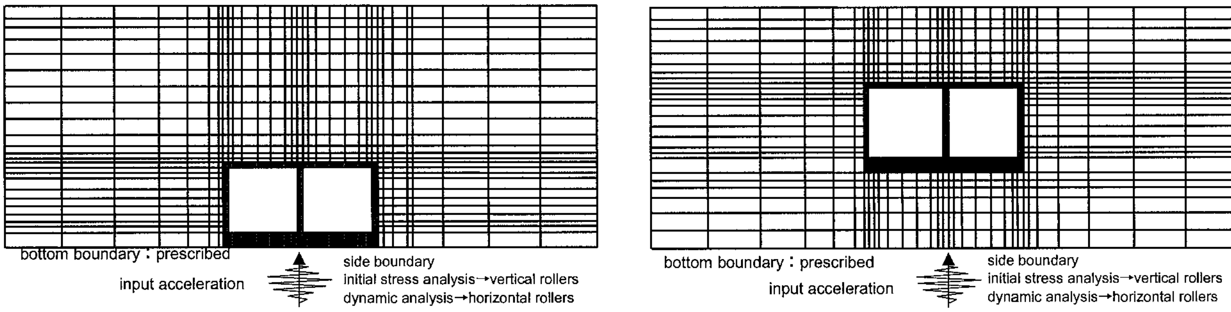
(a) Smeared crack model (b) RC material σ-ε relations (c) nonlinear soil model

Fig.2 Basic Idea of the Method B (Non-linear RC Material Model)

Numerical Models and Properties

FEM models for Fixed and Unfixed cases are depicted in **Fig. 3**. A two-dimensional FEM model was used to satisfy the shake table test conditions. Prescribed condition is assigned for vertical and horizontal directions at the bottom boundary. Vertical and horizontal roller conditions for the side layer boundary are given for initial and dynamic analyses, respectively. In addition, slave node condition is applied for the side layer boundary to maintain appropriate shear deformation of the FEM models. Input motions are defined as a product of incident and reflection waves at the bottom boundary and observed records on the shake table are applied for the FEM model.

Concrete and rebar properties that characterize the RC constitutive law are listed in **Table 1.** Soil properties to identify **Eq. (1)** are also tabulated in **Table 2.** Indeed, these properties were determined by laboratory soil tests to ensure appropriate stress-strain relation in relatively large (approximately 1%) strain level in numerical analysis.



(a) Fixed case (b) Unfixed case

Fig. 3 Arrangement of FEM Mesh

Table 1 Properties for RC

(a) Fixed case

Concrete	Compression strength f'_c (MPa)	33.8
	Tensile strength f_t (MPa)	2.40
	Young's modulus E_c (GPa)	23.5
Rebar	Yield strength f_y (MPa)	265.1
	Young's modulus E_s (GPa)	185

(b) Unfixed case

Concrete	Compression strength f'_c (MPa)	35.2
	Tensile strength f_t (MPa)	2.81
	Young's modulus E_c (GPa)	23.5
Rebar	Yield strength f_y (MPa)	265.1
	Young's modulus E_s (GPa)	185

Table 2 Properties for Soil

(a) Fixed case

Layer (m)	G_0 (MPa)	V_s (m/s)	S_u (kPa)	b
0.00 ~ -1.00	1691	104.4	785	2.21
-1.00 ~ -2.00	3118	141.8	1416	1.63
-2.00 ~ -3.00	4201	164.6	2065	1.41
-3.00 ~ -4.00	5097	181.3	2698	1.28
-4.00 ~ -4.75	5781	193.1	3236	1.20

(b) Unfixed case

Layer (m)	G_0 (MPa)	V_s (m/s)	S_u (kPa)	b
0.00 ~ -1.00	1629	102.5	765	2.25
-1.00 ~ -2.00	3087	141.5	1400	1.64
-2.00 ~ -3.00	4183	164.2	2054	1.41
-3.00 ~ -3.75	4994	179.4	2620	1.29
-3.75 ~ -4.75	5706	191.8	3175	1.21

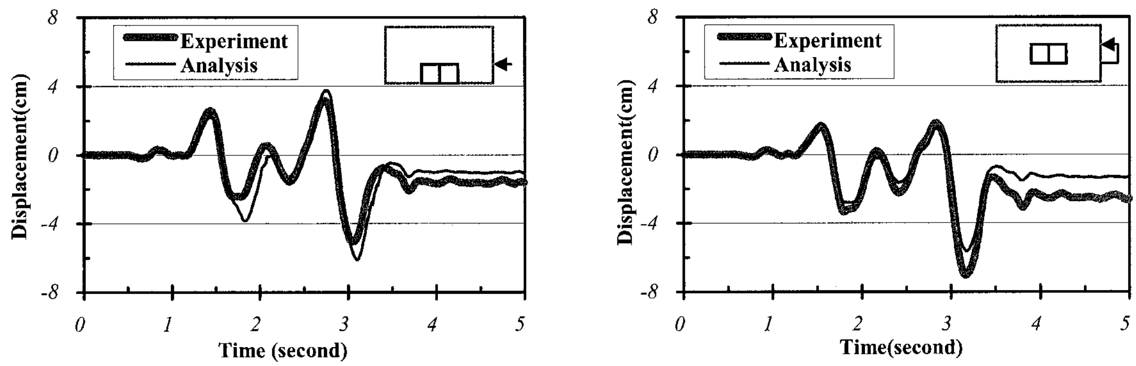
RESULTS AND DISCUSSIONS

Soil-Structure System

Numerical analysis correlation is discussed for both Fixed and Unfixed cases under 1127 and 1041Gal in peak acceleration, respectively.

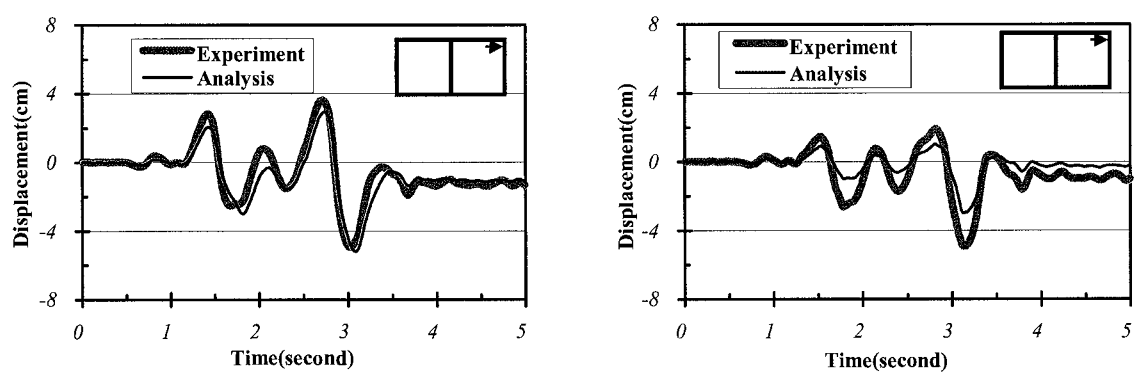
Fig. 4 shows experimental and analytical results of the ground displacements at the side boundary for Fixed and Unfixed cases. Where the ground displacement is defined as relative displacement between the laminar shear box frames that are placed approximately identical height with the model RC structure model. Although the calculated result is somewhat lower than the experimental ones in Unfixed case, the analytical result gives relatively good estimation for the ground displacement. This suggests that modeling of soil stress-strain relationship is considerably appropriate as listed in **Table 2.**

Fig. 5 compares experimental and analytical results for the relative displacement of the model RC structure in time history. Where the relative displacement is defined as the displacement between top and bottom slabs. Hereafter, this definition is used throughout the present paper unless confusion occurs. In Fixed case, the analytical result provides considerably good correlation for phase and peak response. In addition, residual relative displacement is satisfactorily estimated. In Unfixed case, however, the analytical result significantly underestimates the experimental result, particularly in negative peak estimation. This seems to be due to the fact that bond condition for soil-structure interface is applied for the FEM model, although clear slippage between soil and the top slap surface was observed in the Unfixed case. Though more elaborate modeling for Unfixed case is needed, the analytical results are considered to be fair to good, which suggests that the FEM analysis model discussed in the present study appears to be still a powerful tool for practical design purposes.



(a) Fixed 1127Gal case (b) Unfixed 1041Gal case

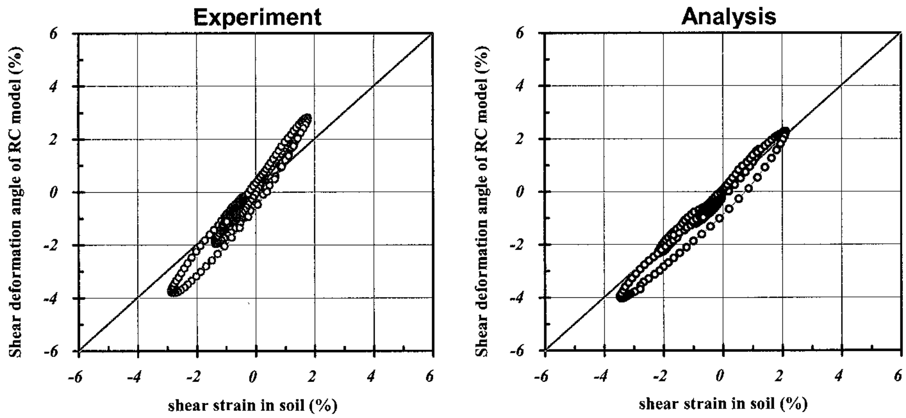
Fig. 4 Time Histories of Ground Displacement



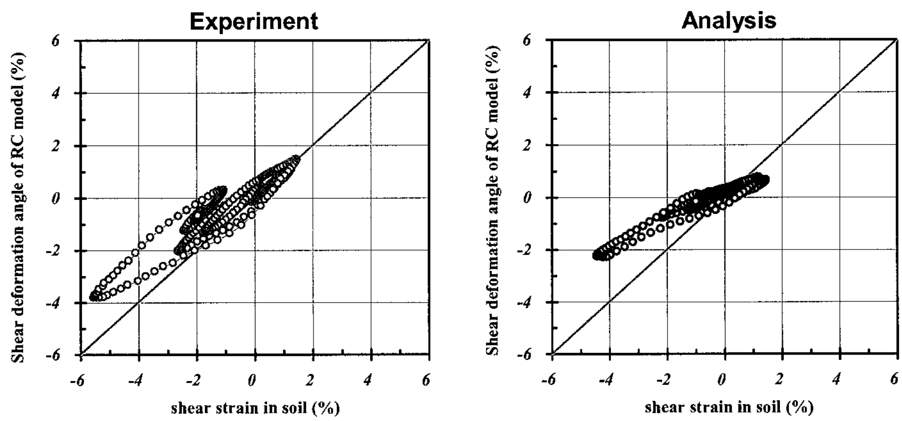
(a) Fixed 1127Gal case (b) Unfixed 1041Gal case

Fig. 5 Time histories of the Relative Displacement

A major difference observed in the numerical analysis correlation between the Fixed and the Unfixed cases is specified as the magnitude of shear deformation of RC models. **Figure 6** presents so-called normalized shear deformation for the model RC structure and soil. In Fixed case, approximately linear relationship is observed for both experiment and analysis. In Unfixed case, larger shear deformation of soils is developed for both experiment and analysis. Although bond modeling is applied for the analysis, identical shear deformation relation is obtained.



(a) Fixed case



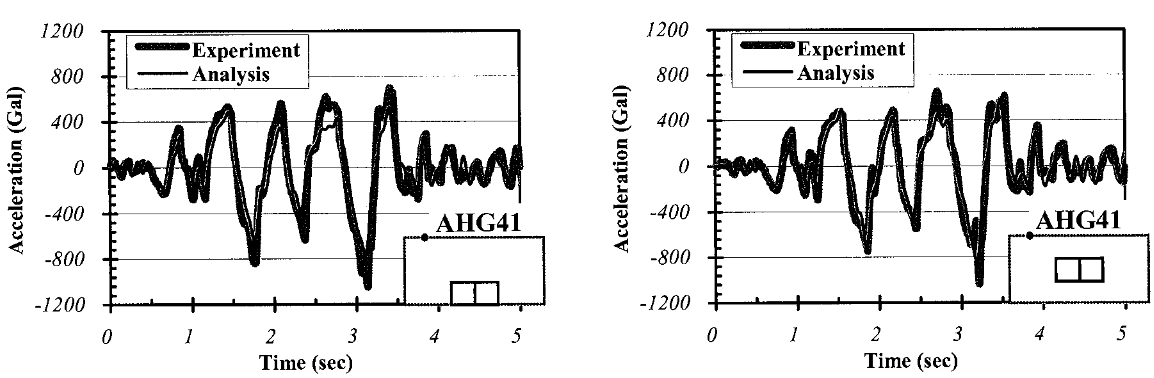
(b) Unfixed case

Fig. 6 Shear Deformation Angle of RC Model with respect to that of Soil

Nonlinear Ground Response

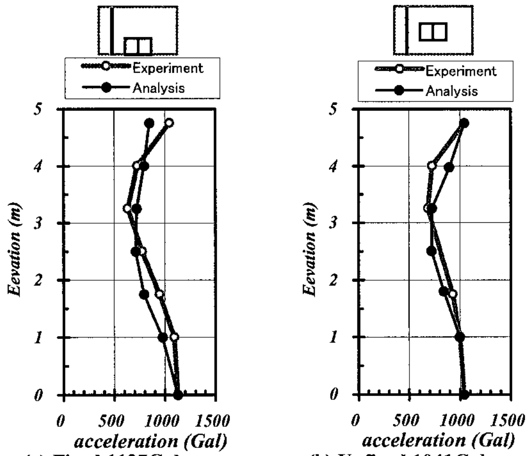
Figure 7 shows experimental and analytical results of the horizontal ground surface acceleration for Fixed and Unfixed cases. Extremely good correlation involving shorter period components is obtained in acceleration time histories.

Figures 8 and 9 illustrate the comparisons of experimental and analytical results for distribution of maximum horizontal acceleration and horizontal displacement. In acceleration response distribution, amplitude reduction with respect to elevation arising from soil nonlinearity can be well explained by the numerical analysis. On the other hand in displacement distribution response, the numerical analysis gives smaller displacement response in shallower part of the laminar shear box. This seems to be as a result of inaccurate estimation of soil nonlinearity under low confining pressure.



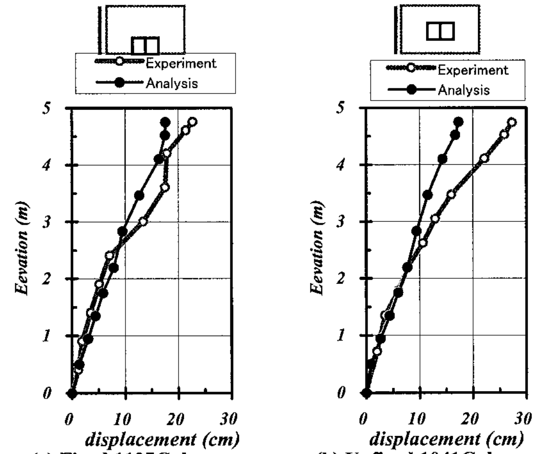
(a) Fixed 1127Gal case **(b) Unfixed 1127Gal case**

Fig. 7 Ground Surface Horizontal Response



(a) Fixed 1127Gal case (b) Unfixed 1041Gal case

Fig. 8 Distribution of Maximum Horizontal Acceleration

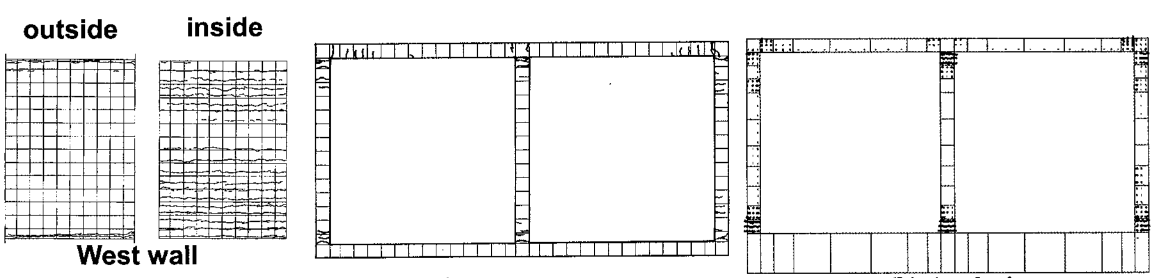


(a) Fixed 1127Gal case (b) Unfixed 1041Gal case

Fig. 9 Distribution of Maximum Horizontal Displacement

Damage Process

Comparisons of observed and analyzed concrete crack patterns are sketched in **Fig. 10**. In the experiment, extensive cracks were localized at the upper and lower corners of RC structure models. As is illustrated in **Fig. 10(a)**, concrete cracks are developed significantly on the inside face of the sidewalls. This is possibly due to the effect of higher degree of compression dynamic earth pressure on the sidewalls during the excitation. These crack behaviors can be well reproduced by the analysis.



(a) Experiment (b) Analysis

Fig. 10 Concrete Crack Patterns (Fixed case)

Locations in observed and analyzed yielding positions in steel are depicted in **Fig. 11** for reversal excitation. Although some discrepancies are found in time order of yielding development, the locations of yielding can be identified fair to well by the numerical analysis. Since yielding phenomena in steel occurred within time interval in 0.01 seconds, in this sense, to analytically estimate such extremely instantaneous events are governed by numerical integration scheme. To identify exactly time order of yielding seems to be a kind of limitation in numerical analysis.

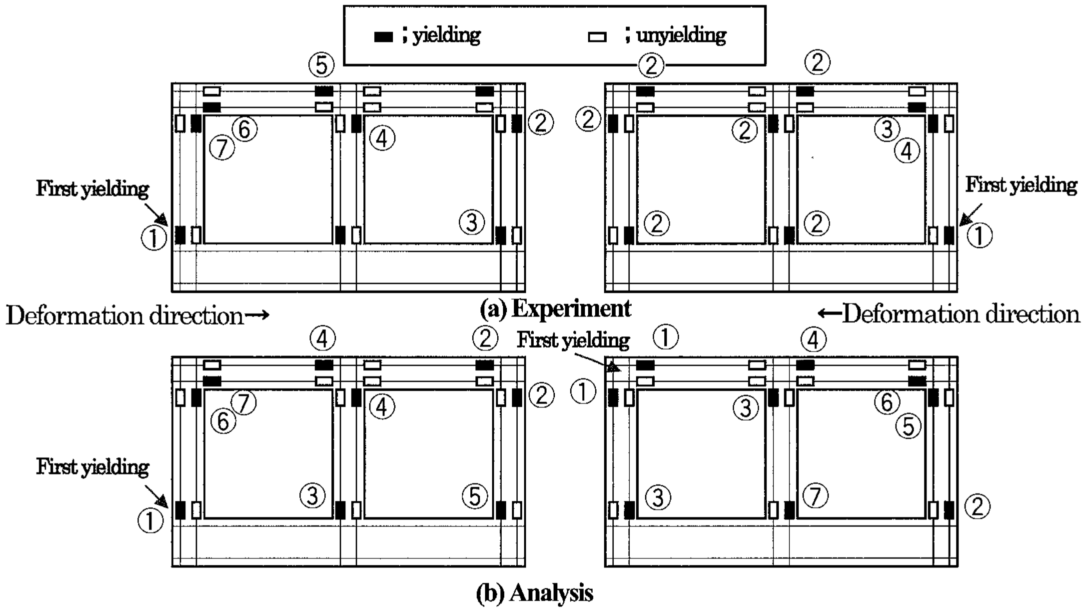


Fig. 11 Locations of Yielding Positions (Fixed case)

Soil-Structure Interaction

Figure 12 compares experimental and analytical results on dynamic earth pressure on the sidewall. In the shake table test [4], the dynamic earth pressure acted in compression manner in spite of cyclic reversed deformation of the model RC structure. In addition, this performance was arising from volume change of soils. Although soil nonlinearity model employed in the numerical analysis incorporates with only linear elastic volume change relation, time histories of the estimated dynamic earth pressure appears to be fair for expressing unique characteristics of the measured dynamic earth pressure.

Figure 13 discusses dynamic shear stress on the top slab surface. As is presented in the previous study [4], this force component is responsible for the degree of plastic deformation of the model RC structure. The numerical analysis provides good correlation with measured dynamic shear stress for both Fixed and Unfixed cases. This supports the fact that the relative displacement of the model RC structure is well estimated as shown in **Fig. 5**.

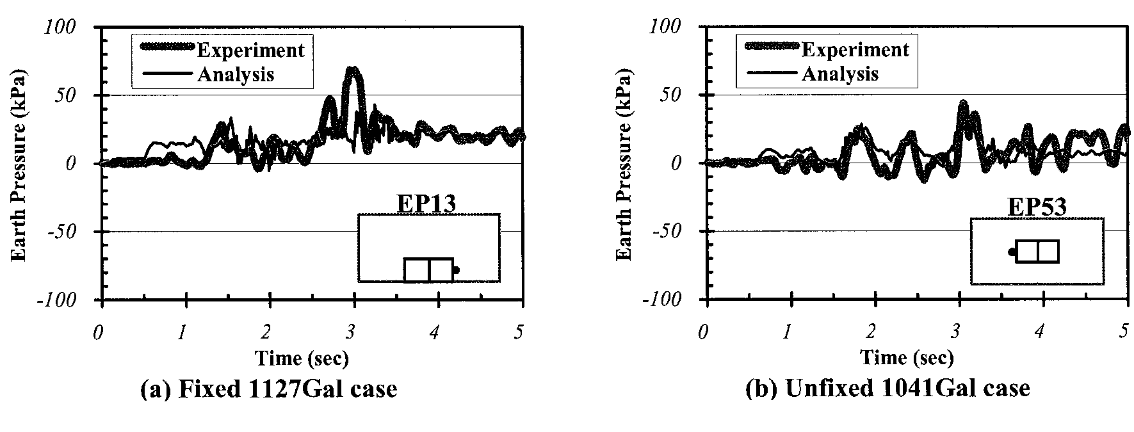
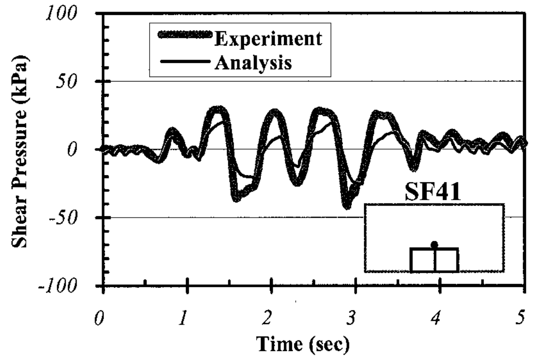
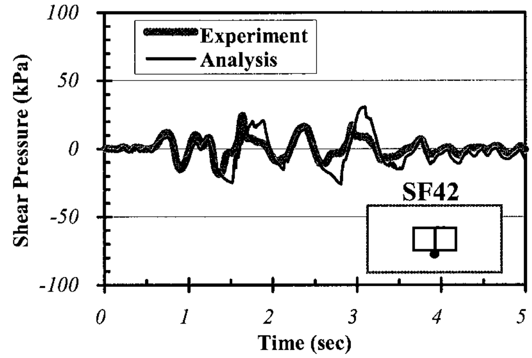


Fig. 12 Dynamic Earth Pressure



(a) Fixed 1127Gal case



(b) Unfixed 1041Gal case

Fig. 13 Shear Stress

CONCLUSIONS

Numerical analysis correlation with the shake table test on plastic deformation performance of the model RC structure is discussed. The nonlinear FEM analysis code that incorporates with RC constitutive laws and hysteretic dependent soil stress-strain relationship is applied for this purpose. The accuracy of the numerical analysis is examined in regard to ground response, structure deformation and dynamic soil-structure interaction. Thanks to appropriate model parameters incorporetd in the soil nonlinear model, the numerical analysis is found to have an acceptable estimation for nonlinear ground response. With this advantage, the degree of plastic deformation and damage process of the model RC structures is successfully estimated, particularly in Fixed case. This is believed to be due to the fact that the model RC structure performance is totally governed by surrounding soil deformation during the shake table test. In addition, dynamic soil-structure interaction effects such as dynamic earth pressure on the sidewall and shear stress on the top slab are numerically correlated with measured results. Although the soil nonlinear mode excludes soil volume change, i.e. dilatancy effect, the numerical analysis gives fair estimation on dynamic earth pressure. On the contrary, estimated shear stress is considered to be well correlated with experimental result. This also supports that degree of the structure deformation is satisfactorily evaluated. Unbond interface condition, which is essential to express possible slippage and/or separation, is needed to discuss in deep the accuracy of the nonlinear FEM model. The effort for this issue is currently under way.

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