Soil-Structure Interaction Effects on Building Response in Recent Earthquakes

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The soil-structure interaction effects on the earthquake response of buildings are studied by carrying out a simulation analysis of the buildings suffered no structural damage during the 1995 Hyogoken-Nanbu Earthquake and parametric earthquake response analyses using representative ground motion records of the recent domestic or foreign big earthquakes. From these analyses, it is pointed out that the damage reduction effects by soil-structure interaction greatly depend on the ground motion characteristics, number of stories and horizontal capacity of earthquake resistance of buildings. Consequently, it is very important to consider soil-structure interaction including nonlinear phenomena such as base mat uplift to evaluate the earthquake damage of buildings properly.

INTRODUCTION

We have experienced several severe earthquake disasters in recent years. In those earthquakes, many modern buildings were severely damaged with various types of patterns. Such building damage has been extensively studied especially from structural points of view. The consideration of the soil-structure interaction (SSI) effects may alter the interpretation of damage as well as the seismic performance of buildings. The purpose of this paper is to examine the soil-structure interaction effects on the earthquake response of buildings during large earthquakes.

First, a slender building located in the heavily damaged area in the 1995 Hyogoken-Nanbu, Japan, Earthquake is given as an example which did not suffer any structural damage probably due to uplifting motion (Hayashi (1996a), (1999)).

Next, in order to examine the influence of SSI effects on the interpretation of the damage, parametric earthquake response analyses using representative ground motion records during the Kobe earthquake and Taiwan Chi-Chi Earthquake are performed. In the studies, simple sway-rocking models are used and non-linearity of buildings is considered so that the SSI effects can be simply introduced.

Through these two kinds of analyses, the damage reduction effects of SSI are investigated.

SIMULATION OF A SLIGHTLY DAMAGED SLENDER BUILDING DURING THE KOBE EARTHQUAKE

In this section, we will show an example of the case that a slender building did not suffer any structural damage, even though it locates in the heavily damaged area of Kobe in the 1995 Hyogoken-Nanbu Earthquake (Hayashi (1996a), (1999)).

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Outline of the Building and Input Motion

The building to be considered is an office building which has 9 stories above the ground level and one below, and whose height is 31m and has a five-cornered plan shape with the dimension of 10m×12m. The foundation is spread foundation and embedded to 6m depth. The superstructures are composed of SRC moment-resisting frames with RC shear walls. This building was built after 1981 when the new building code was established. The ultimate lateral strength coefficient of the building is estimated to be 0.8 at the first floor. This value is calculated from the design drawings using the second screening method in the standards (The Japan Building Disaster Prevention Association, 1983). This building suffered no structural damage except for some hair cracks on a non-structural RC wall around the elevator shaft. However, gaps about 1-3cm wide were observed between underground exterior walls and the surrounding soil. From the fact, the uplift of the base mat and the separation between the foundation and the soil occurred during the earthquake was estimated.

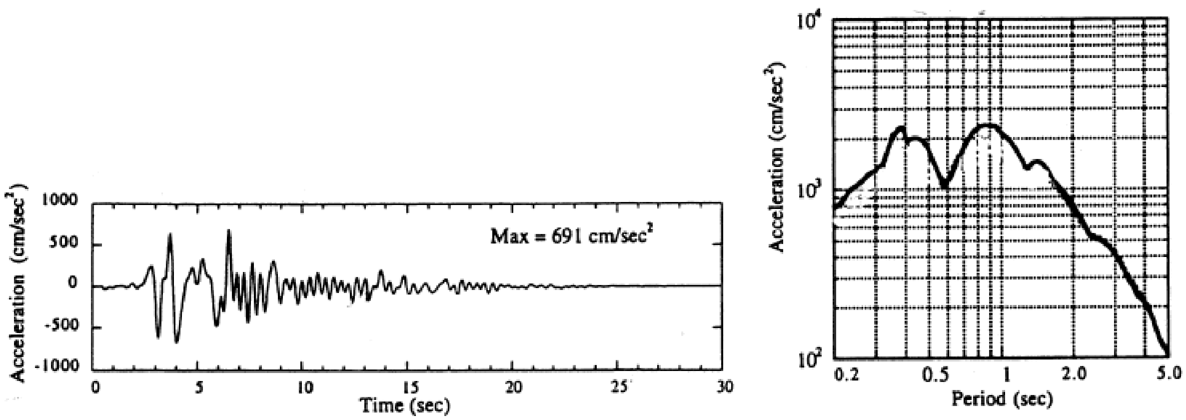


Figure 1 Time history (left) and acceleration response spectrum (right) of input motions (Figures reprinted from Hayashi, 1999.)

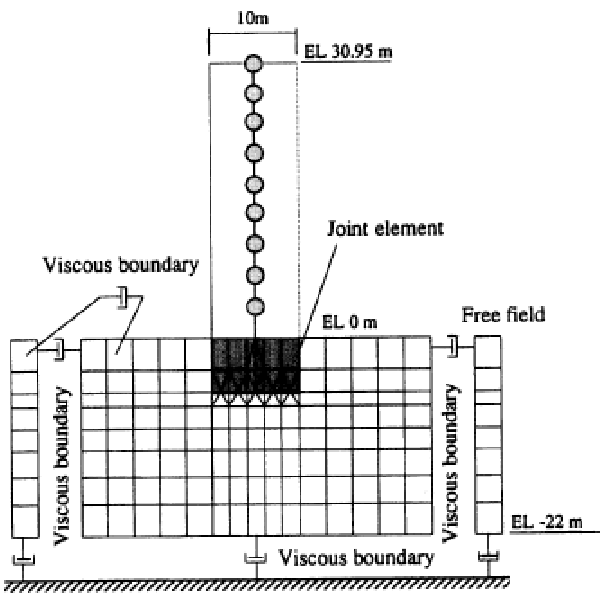
Input motions for the simulation analyses are the estimated outcrop motions converted from the strong motion records observed at JMA-Kobe, using 2-D FEM ground model (Hayashi 1996b). The maximum acceleration of the input motions is 691cm/s^2. The time history and response spectrum of the input motions are depicted in Fig. 1.

Analysis Model

To take account of the phenomena of the base mat uplift and separation between the underground exterior walls and the soil, we adopted a 2-D FEM model with joint elements (Fig. 2). The building model has linear springs and its underground stiffness is assumed to be rigid. The mass and linear stiffness of shear springs of the building model are also denoted in the same figure. The soil is to be equivalent linear and soil properties are listed in Table 1. The bottom level of the FEM region is GL-22m and viscous boundaries are attached to both sides and at the bottom, respectively, to express outgoing waves. The response analyses both with and without uplifting using this model are carried out.

Table 1 Soil profile

Layer no.	Depth (m)	Soil type	Shear wave velocity Vs(m/s)	Damping factor h'	Max.s strain (%)
1	0-3.5	Corse sand	184	0.13	0.055
2	3.5-6.0	Corse sand	219	0.12	0.1
3	6.0-7.6	with gravel	243	0.08	0.12
4	7.6-12.7	Corse sand	110	0.18	0.86
5	12.7-15.6	Corse sand	94	0.20	1.5
6	15.6-18.7	Corse sand	90	0.20	1.9
7	18.7-	Fine sand	450	0.03	--



Floor	Level (m)	Mass (ton)	Stiffness (tonf/cm)
R	31.0	291	
9	27.7	190	213
8	24.3	195	208
7	21.0	193	189
6	17.6	193	243
5	14.3	197	247
4	10.9	205	257
3	7.5	208	284
2	4.0	223	308
1	0.0	267	241
B1	-4.0	582	large

Figure 2 Finite element model of SSI system (left) and analysis model for super structure (right) (Figures reprinted from Hayashi, 1999.)

Results of Simulation Analysis and Discussion

Figure 3(a) shows the distribution of maximum lateral force coefficients obtained from the response analyses. The response of the model with uplift is about two thirds to half of that without uplift. The response level of the building reaches the same level as the ultimate capacity of the building in the case with considering base mat uplift.

Figure 3(b) shows the distribution of maximum rotational angles. The thick lines with symbols show the rotational angle at each floor, which is calculated by the horizontal displacement divided by the height of the floor from the ground level. The thin lines are rotational angles of the foundation. The rotational angle at each floor does not vary much among analysis cases, however, the rotational angle of the foundation drastically increased in the case of considering base mat uplift. Therefore, inter-story deformation was reduced by increases of the foundation rotational angle. From these results, it can be estimated that the uplifting effects are the main reason why the slender building did not suffer any structural damage.

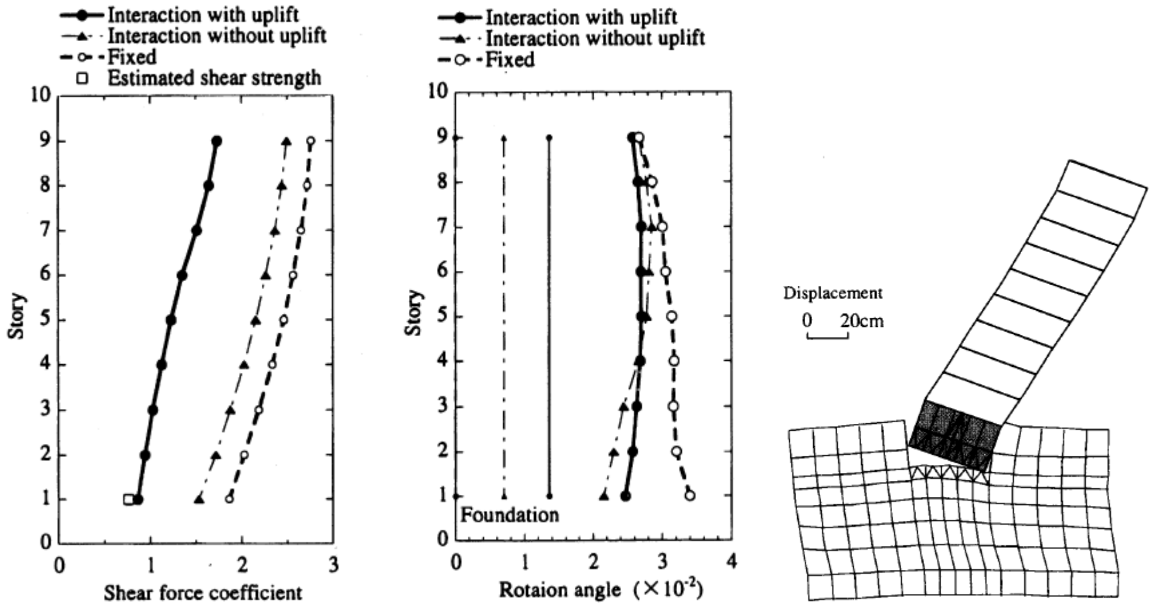


Figure 3. Maximum response values of (a) shear force coefficient, (b) rotational angle and (c) deformation in uplift state. (Figures reprinted from Hayashi, 1999.)

RESPONSE ANALYSES BASED ON OBSERVED GROUND MOTIONS

In this section, effectiveness of SSI in earthquake response reduction of buildings is studied by parametric earthquake response analyses using the representative ground motion records of recent domestic or foreign big earthquakes.

We uses two type of response analysis models; fixed foundation models (FIX model) and sway-rocking models (SSI model). The height of all stories is 4m, and fundamental period T of FIX models with the number of stories N is given by T=0.08N. The superstructure of buildings is simplified to a SDOF system by assuming the inter-story displacement of the first mode to be constant. Damping factor is proportional to instantaneous stiffness and is equal to 0.03 for the superstructure. Nonlinearity of superstructure is expressed by tri-linear skeleton curve with a hysteresis rule of Takeda model (Takeda, 1970). Yield base shear coefficient C_y is parametrically changed as $C_y = \gamma / N$ using parameter γ by taking the C_y is almost inversely proportional to the number of stories N into account. Since the γ of most RC buildings with N=2 to 5 ranges from 3 to 5 in Japan, γ is set to 2 or 5 in this study.

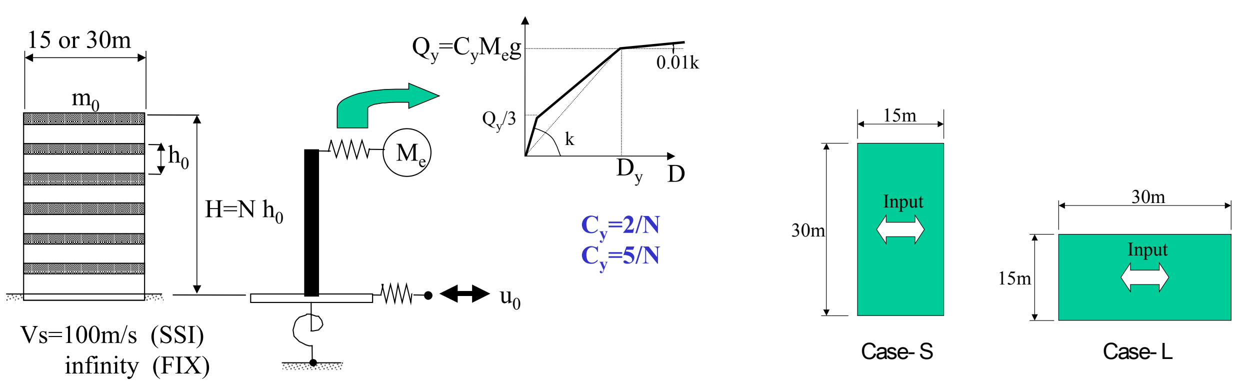


Figure 4 Analysis model of parametric analyses using observed ground motions (left) and input direction (right).

The sway-rocking (SSI) models are developed based on the following assumptions. Rectangular direct foundation with the dimension of 15m×30m is rest on the soil surface. Earthquake ground motions are input in the longitudinal direction (Case-L) or transverse direction (Case-S). In case of apartment houses or school buildings, horizontal resisting capacity in the transverse direction is much higher than that in the longitudinal direction due to the existence of walls in the transverse direction. The soil is assumed to be semi-infinite and homogeneous. The shear wave velocity *Vs* is set to be 100 m/s or 200m/s. Soil nonlinearity is neglected because of simplicity of our analyses and understanding, although the drastic decrease in shear wave velocity during the severe ground motions are implicitly estimated.

Figure 5 shows the natural period *T* for FIX models and SSI models. Increase in *T* by considering SSI effects become evident as shear wave velocity *Vs* decreases. As for the cases for *Vs* =100m/s, the ratio of natural periods for SSI models to those for FIX models is more than 2 in the transverse direction and 1.5 in the longitudinal direction.

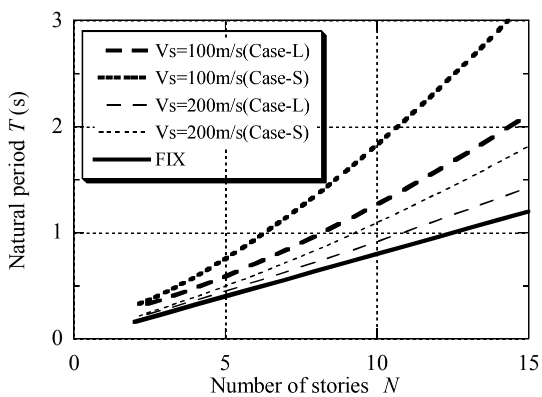


Figure 5 Natural period of SSI and FIX models

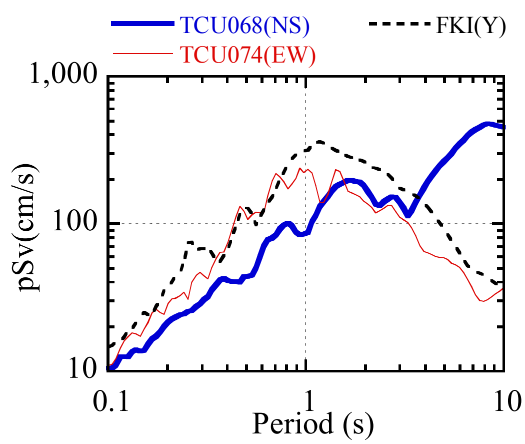


Figure 6 Response spectra

1995 Hyogoken-Nanbu, Japan, Earthquake

First, response analyses are performed using an the observed ground motion records at the Fukiai Gas station (FKI), which is located in the most heavily damage area in the Hyogoken-Nanbu, Japan, Earthquake of 1995. Figure 7 shows the relationship between the maximum response R_{max} of shear deformation angle *R* and the number of stories. Solid and dashed lines correspond to γ=2 and γ=5, respectively. Thick and thin lines correspond to SSI and FIX models, respectively. Time histories of shear deformation angle *R* for the 5-story building with γ=2 obtained from the FIX models and SSI models are compared in Fig. 8.

As for Case-L shown in Fig. 7(a), R_{max} is greatly dependent on horizontal resisting capacity rather than consideration of SSI effects especially for buildings of 4 or less stories. If the horizontal resisting capacity is small, nonlinear deformation progresses rapidly under severe impulsive earthquake ground motions before soil-structure interaction effects emerge as shown in Fig. 8.

As for Case-S shown in Fig. 7(b), difference in R_{max} of 8 to 12-story buildings become clear by considering SSI effects, if horizontal resisting capacity is large (γ = 5).

If we neglect the SSI effects, we may not explain the damage situation of apartment houses with rectangular plan and 8-12 stories, whose horizontal resisting capacity in the transverse direction is usually high due to the existence of walls in the transverse direction. Therefore, the soil is assumed to be semi-infinite and homogeneous.

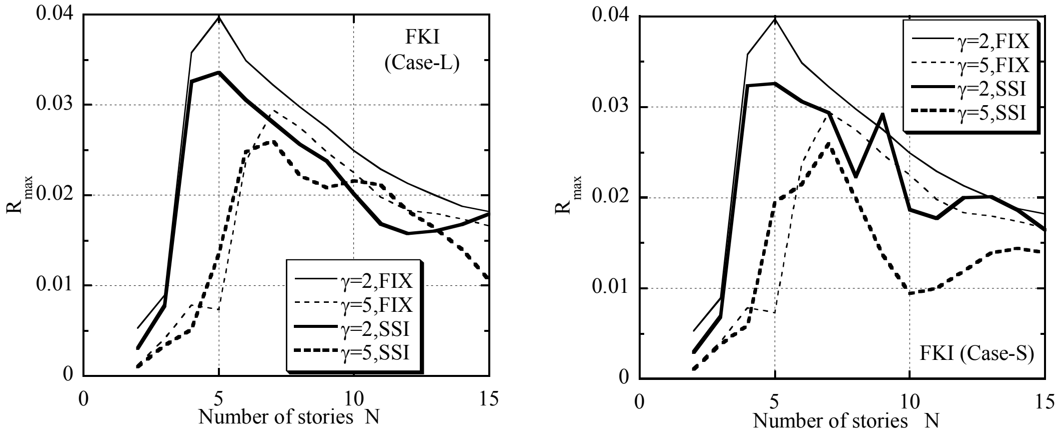


Figure 7 Maximum shear deformation angle (FKI, 1995 Hyogoken-Nanbu, Japan, EQ.)

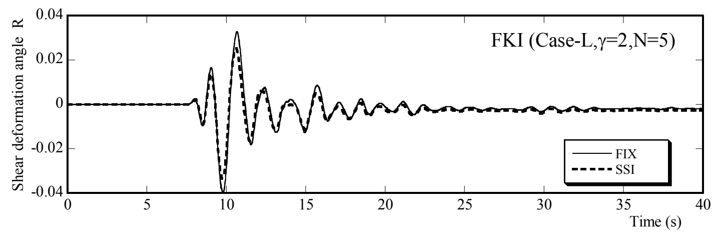


Figure 8 Time history of shear deformation angle (FKI, 1995 Hyogoken-Nanbu EQ.)

1999 Chi-Chi, Taiwan, earthquake

Next, results of response analyses using observed records at TCU068 and TCU074 stations during the Chi-Chi earthquake of 1999 are shown. Although large fault movement was found near the TCU068 station after the earthquake, few low-rise buildings suffered serious damage due to ground motions. On the other hand, a large number of low-rise buildings including school buildings are severely damaged around TCU074 stations. Figure 9 shows the relationship between the maximum shear deformation angles R_{max} and the number of stories. Figure 10 shows the time histories of shear deformation angles for 7-story building.

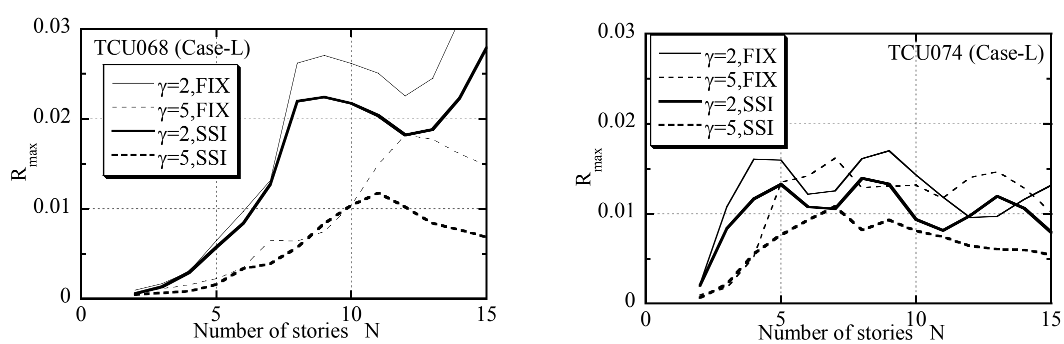


Figure 9 Maximum shear deformation angle
(TCU068(left) and TCU074(right), 1999 Chi-Chi, Taiwan, EQ.)

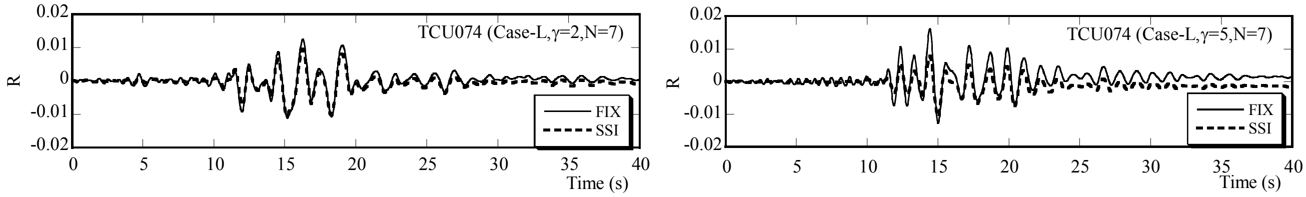


Figure 10 Time history of shear deformation angle
(γ=2(left) and γ=5(right), CASE-L, TCU074, 1999 Chi-Chi, Taiwan, EQ.)

Difference in R_{max} of FIX and SSI models is not evident for buildings of 7 or less stories subjected to the ground motion at the TCU068 station. Then, the R_{max} of 5 or less story buildings is small and less than 0.005. Therefore, the damage situation of low-rise buildings around the TCU068 station can be explained without considering SSI. The R_{max} increases with the number of stories. If there were many 8 or more story buildings around the TCU068 station, the buildings would have suffered serious damage including collapse. It is noticeable that the difference in R_{max} of FIX and SSI model for buildings of 10 or more stories is very large if the horizontal resisting capacity is large (γ=5). The consideration of the SSI effects would have played an important role to understand the damage situations.

As for the TCU074 case, similarly, the maximum shear deformation angle is greatly reduced by considering SSI effects. The minimum number of stories N_{min}, where the SSI effects are remarkable, is 4 while N_{min} for TCU068 is about 8. Namely the SSI effects are considered to be affected by frequency characteristics of ground motions used in the response analysis.

CONCLUSIONS

To examine the effectiveness of soil-structure interaction in earthquake response reduction of buildings, a simulation analysis of a slender building was not suffered any structural damage during the 1995 Hyogoken-Nanbu Earthquake and parametric earthquake response analyses using representative ground motion records of recent domestic or foreign big earthquakes were carried out.

The following conclusions can be drawn.

1. From the response analyses of a slender building using a 2-D FEM model taking basemat uplift into consideration, uplifting was considered to be the main reason why it did not suffer any structural damage. In order to grasp the seismic performance of buildings subjected to very severe ground motions, we should consider nonlinear soil-structure interaction effects such as uplifting properly.
2. From the parametric analyses using recorded ground motions, it is pointed out that the earthquake response reduction effects by SSI are strongly affected by the horizontal resisting capacity of buildings, the number of stories and characteristics of ground motions such as predominant frequency and seismic intensity. In order to interpret the damage or seismic performance of slender mid-rise buildings, the appropriate evaluation of soil-structure interaction effects and horizontal resisting capacity is very important.

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