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Analytical Study on Damping Effect of Building Considering Dynamical Interaction between Soil and Building

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Abstract

It has been pointed out that the damping effect related to building dynamic response characteristics due to the interaction between soil and building is of relatively significant influence. Usually, we want to know the damping effect on the dynamic interaction between the soil and the building taking into consideration the combination of the soil conditions and building dimensions depending on the foundation type. We therefore performed parametric case studies using SDOF building models which have different stories from 2 to 32 stories with a changing natural period, while also taking into consideration the foundation type (direct foundation type or pile foundation type) and surrounding soil conditions (depth and stiffness of surface layer). We divided the combination conditions between the foundation dimensions and building type (divided into 3 types: low, middle and high rise building types according to building stories) and soil conditions (divided into 3 by depth and stiffness of soil layer). The natural period of the building is assumed by the formula used in the Japanese building design code.

In the first step, we calculated the impedance between the soil and the building according to the combination conditions with the differences of foundation type by using the results of the impedance analysis. Then, we performed the dynamic response calculation by using Sway-Rocking (S-R) model introducing the spring and damping constants of sway and rocking motion obtained from the impedance in each combination condition. In this calculation process, we assumed two kinds of S-R Model, one being the actual S-R Model (S-R_{act} Model) with actual spring and damping constants obtained from impedance analysis and the building inner damping fixed to 2% (h=0.02) and the other was the revised S-R Model (S-R_{rev} Model) which has only the spring constant obtained from the impedance analysis but ignoring the damping constant and the building inner damping h is variably changed.

In the second step, we performed the dynamic response calculation using the S-R_{act} Model and the S-R_{rev} Model with all assumed building types from 2 to 32 stories by checking the similarity of the maximum acceleration response values at the top of buildings. Comparing the maximum response value between the S-R_{act} Model and the S-R_{rev} Model, we obtained the building inner damping constant h of the S-R_{rev} Model which gives same effect on the building response due to the interaction between soil and building.

In this paper, we performed two analytical studies, one was the case of a building foundation without piles, and the other case was a building foundation with piles. We would like to present the results on the apparent effect of damping due to the interaction between soil and building.

In conclusion, in the case of a direct foundation, the result of building inner damping constant decreased according to the number of building stories: and the higher the building, the longer the natural period, t, and the less the interaction combination effect between the soil and the building, and conversely, the higher the building, and the shorter the natural period, and the interaction combination effect increases markedly. Otherwise, in the case of a pile foundation, the results showed a larger damping constant, namely, it showed a greater damping effects due to the dynamic interaction between the soil and the building, namely dispersed damping effects largely appeared in the case of a pile foundation.

Keywords: Damping Effect, Dynamical Interaction, S-R Model, Soil and Building System

1. Introduction

It has been pointed out that the damping effect related to building dynamic response characteristics due to the interaction between soil and building is of relatively significant influence. Historically, the interaction phenomena were investigated in several ideas and methods [1, 2, 3, 4, 5, 6] and introduced the theoretic analysis method [7]. Recently, the data base of damping factor of buildings was summarized and published [8]. We investigated the seismic response of building considered the interaction between soil and building by observed seismic records [9].

Usually, we want to know the damping effect on the dynamic interaction between soil and building taking into consideration the combination of the soil conditions and building dimensions depending on the foundation type. We therefore performed parametric case studies using SDOF building models which had different stories from 2 to 32 stories with a changing natural period, and also took into consideration the foundation type (direct foundation type or pile foundation type) and the surrounding soil conditions (depth and stiffness of surface layer). We divided the combination conditions between the foundation dimension with the building type (divided into 3 types: low, middle and high rise building type depending on the number of building stories) and soil conditions (divided into 3 by depth and stiffness of soil layer). The natural period of the building was assumed by the formula used in the Japanese building design code. First, we calculated the impedance between soil and building dependent on combination conditions according to the foundation type by using the results of impedance analysis. Then, we performed the dynamic response calculation using the Sway-Rocking (S-R) model introducing the spring and damping constants of the sway and rocking motions obtained from the impedance in each combination condition. In this calculation process, we assumed two kinds of S-R Model: one was the actual S-R Model (S-R_{act} Model) with actual spring and damping constants obtained from the impedance analysis and the building inner damping fixed to 2% (h=0.02) and the other was the revised S-R Model (S-R_{rev} Model) which have only the spring constant obtained from the impedance analysis but the damping constant was ignored and the building inner damping h was variably changed. Second, we performed the dynamic response calculation using the S-R_{act} Model and the S-R_{rev} Model with all assumed building types from 2 to 32 stories by checking the similarity of maximum acceleration response values at the top of buildings.

2. Analytical Method in Case of Direct Foundation

2.1 Setting of Buildings, Soils, and Foundations

2.1.1 Setting of Building Model

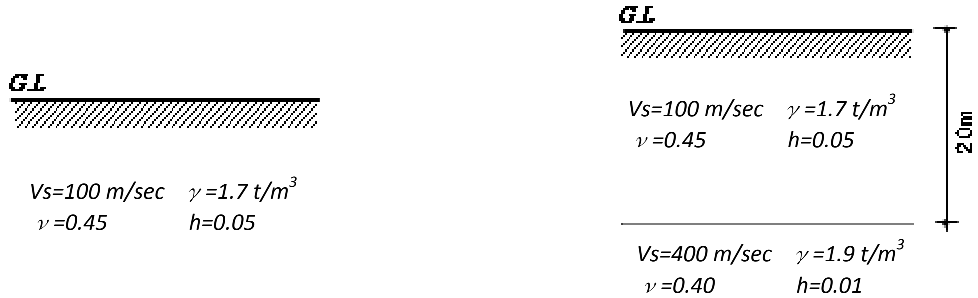
Building Models were from 2 to 36 stories and basically, they are divided into three categories: low rise, middle rise, and high rise building groups. The low rise building group included buildings from 2 stories to 13 stories, the middle rise building group included buildings from 14 stories to 26 stories, and the high rise building group was from 27 stories to 36 stories as indicated in Table 1.

Table 1 Settled Condition for Assumed Building

	Condition	Classification of Building Groups
Structure	RC	Number of Stories on Assumed Building ・Low Rise Building Group 2 – 13 stories ・Middle Rise Building Group 14 – 26 Stories ・High Rise Buuilding Group 27 – 36 Stores
Height of Story	3.0 m	
Weight of Story	13.0 kN/m2	

2.1.2 Setting of Soil Structure Model

The soil structure model was considered as two types: G1 and G2, as indicated in Fig. 1. Model G1 is a single-layered homogeneous half space soil structure and Model G2 is double-layered soil structure, the second (lower) soil layer being a half space layer.

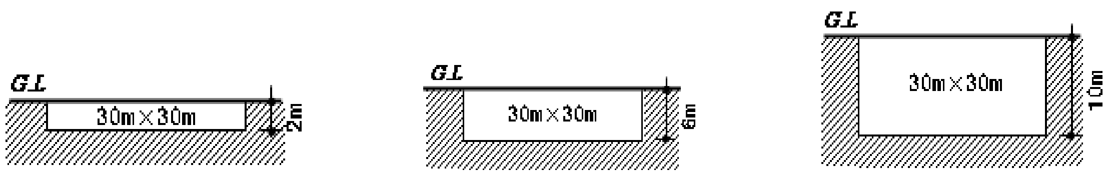


(a) Homogeneous Soil Structure Model [G1]   (b) Two Layered Soil Structure Model [G2]

Fig. 1 Assumed Soil Structure Models

2.1.3 Setting of Foundation System

Usually, building foundation systems vary according to the building and soil structure. The scale and dimension increases according to the height of building, namely the number of building stories. So, we set the foundation dimensions to change by three types as indicated in Fig. 2, Model R1 was for the low rise building group, Model R2 was for the middle rise building group, and Model R3 was for the high rise building group.



(a) Foundation System for Low Rise Building Group [R1]   (b) Foundation System for Middle Rise Building Group [R2]   (c) Foundation System for Low Rise Building Group [R3]

Fig. 2 Assumed Foundation Model

2.1.4 Setting of Analyzed Cases

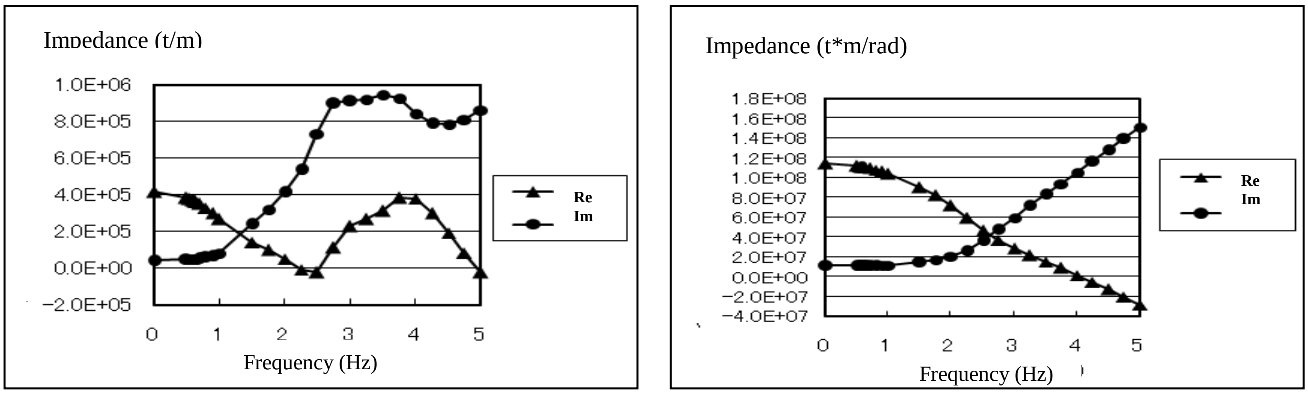
We took into consideration the three building groups (low, middle and high rise building groups as mentioned in 2.1.1), two soil structure models (Model G1 and Model G2, as mentioned in 2.1.2) and also three types of building foundation dimensions (Model R1, R2 and R3). Finally, we analyzed six cases taking into consideration the combination of building group, soil structure, and also building foundation dimensions. Six cases of analysis are indicated in Table 2.

Table 2 Analyzed Cases of Soil and Foundation Combination in Case of Direct Foundation

	Soil Structure	Foundation System
CASE 1	G2	R1
CASE 2	G2	R2
CASE 3	G2	R3
CASE 4	G1	R1
CASE 5	G1	R2
CASE 6	G1	R3

2.2 Calculation of Impedance and Converged Natural Period

We calculated the impedance for the dynamic interaction between the building foundation and surrounding soil by using a 3D FEM program. For example in Case 2, we calculated the impedances for the horizontal direction and rotational directions. Impedance function is shown in Fig. 3. Using these impedances, we could evaluate the spring constants for the horizontal movement direction and rotational movement direction, and also, the damping constant for both movement directions by equations (1) and (2), respectively.



(a) Horizontal Direction (b) Rotational Direction

Fig. 3 Impedance Functions

$$h_H = \sin(0.5(\tan^{-1}(\mathrm{Im}(K_H')/\mathrm{Re}(K_H')))) \quad (1)$$

$$h_R = \sin(0.5(\tan^{-1}(\mathrm{Im}(K_R')/\mathrm{Re}(K_R')))) \quad (2)$$

Where, *h* ; Damping Constant, *H* means the horizontal component and *R* means the rotational component

K'; Impedance, *H* means the horizontal component and *R* means the rotational component

Re(*K'*) ; Real Part of Impedance *K'*

Im(*K'*) ; Imaginary Part of Impedance *K'*

In order to investigate the influence of the damping effect due to the dynamic interaction between building foundations and soils, in the first analysis step, we considered two analytical models, one was a foundation fixed model (FIX Model) and the other was a Sway-Rocking Model (S-R Model) with SDOF (Single Degree of Freedom) for the upper building, which have from 2 to 36 stories, respectively. These models are indicated in Fig. 4.

Usually, the natural period of a building for the FIX Model is evaluated by equation (3).

$$T=0.07\times N \quad (3)$$

Where, T is the natural period of the building and N is the number of building stories (N=2 - 36).

Using the S-R Model we tried to evaluate the natural period of the building and soil system by interaction method until the values converged.

For the initial condition of building characteristics, we determined that the natural period of the building was a value calculated by equation (3), and building inner damping constant was 2%, namely h=0.02. Then we evaluated the natural period of the building-soil system with interaction using the S-R Model indicated in Table 3 and 4.

Table 3 Natural Period of S-R_{act} Model and Converged Natural Period of S-R_{rev} Model for One Layer Soil Structure Model G1

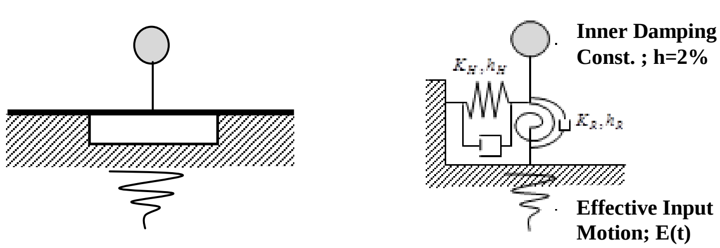
CASE 4			CASE 5			CASE 6		
N	T	T'	N	T	T'	N	T	T'
2	0.11	0.47	14	0.77	1.46	27	1.50	3.18
3	0.17	0.51	15	0.83	1.57	28	1.55	3.33
4	0.22	0.58	16	0.88	1.68	29	1.61	3.47
5	0.28	0.62	17	0.94	1.79	30	1.67	3.61
6	0.33	0.69	18	1.00	1.90	31	1.72	3.76
7	0.39	0.75	19	1.05	2.01	32	1.78	3.91
8	0.44	0.82	20	1.11	2.13	33	1.83	4.03
9	0.50	0.90	21	1.17	2.23	34	1.89	4.18
10	0.55	0.98	22	1.22	2.36	35	1.94	4.34
11	0.61	1.07	23	1.28	2.49	36	2.00	4.45
12	0.66	1.16	24	1.33	2.71			
13	0.72	1.25	25	1.39	2.76			
			26	1.44	2.87			

N: Number of Building Stories
T: Natural Period of Building in S-R_{act} Model
T': Converged Natural Period of Building in S-R_{rev} Model

Table 4 Natural Period of S-R_{act} Model and Converged Natural Period of S-R_{rev} Model for Two Layered Soil Structure Model G2

CASE 1			CASE 2			CASE 3		
N	T	T'	N	T	T'	N	T	T'
2	0.11	0.28	14	0.77	1.25	27	1.50	2.43
3	0.17	0.40	15	0.83	1.33	28	1.55	2.52
4	0.22	0.49	16	0.88	1.41	29	1.61	2.61
5	0.28	0.54	17	0.94	1.50	30	1.67	2.70
6	0.33	0.60	18	1.00	1.59	31	1.72	2.79
7	0.39	0.66	19	1.05	1.68	32	1.78	2.89
8	0.44	0.73	20	1.11	1.77	33	1.83	2.98
9	0.50	0.81	21	1.17	1.87	34	1.89	3.08
10	0.55	0.88	22	1.22	1.97	35	1.94	3.19
11	0.61	0.95	23	1.28	2.07	36	2.00	3.29
12	0.66	1.05	24	1.33	2.17			
13	0.72	1.14	25	1.39	2.28			
			26	1.44	2.39			

N: Number of Building Stories
T: Natural Period of Building in S-R_{act} Model
T': Converged Natural Period of Building in S-R_{rev} Model



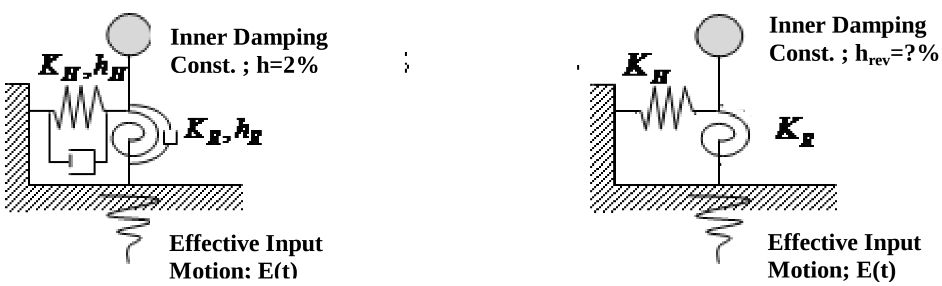
(a) FIX Model (b) S-R Model

Fig. 4 Two Analytical Models, (a)FIX Model and (b)S-R Model

2.3 Earthquake Response Analysis

In order to evaluate the damping effect due to the dynamic interaction between building and soil, we used two different S-R models, namely, an ordinal type S-R model as indicated in Fig. 5(a) indicated as S-R_{act} which set horizontal and rotational spring constants K_H, K_R and damping constants h_H, h_R calculated from impedance analysis and also the effective input motion E(t).

The other S-R model set only the spring constants K_H, K_R and excluded the damping constants h_H, h_R, namely S-R_{rev} model, as indicated in Fig. 5(b). In both cases we took into consideration that the natural period of the S-R_{act} and S-R_{rev} models set the converged period indicated in Table 3 according to the number of building stories. We then evaluated the damping effect due to the dynamic interaction by changing the inner damping constant value while adjusting the same response value in both cases obtained from response simulation used in the S-R_{act} and S-R_{rev} model, respectively.



(a) Actual S-R Model : S-R_{act} Model (b) Revised S-R Model : S-R_{rev} Model

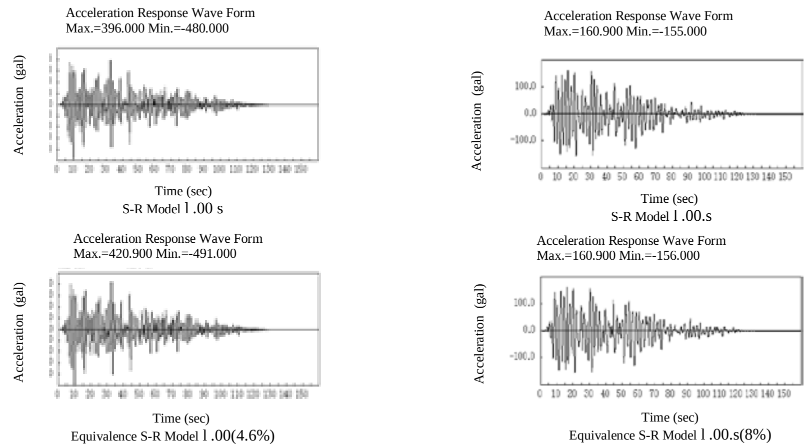
Fig. 5 SDOF Model with Soil-Structure Interaction used S-R Model
((a): Actual S-R Model, (b): Revised S-R Model)

2.4 Analysis Results

We performed the response analysis by using the RESP-II program for the S-R_{act} and S-R_{rev} models. In the case of the S-R_{rev} model, we performed the calculation changing the inner damping of the building hrev; h_{rev} signifying the revised inner damping constant with the effect of the interaction between building and soil and it’s expressed as follows.

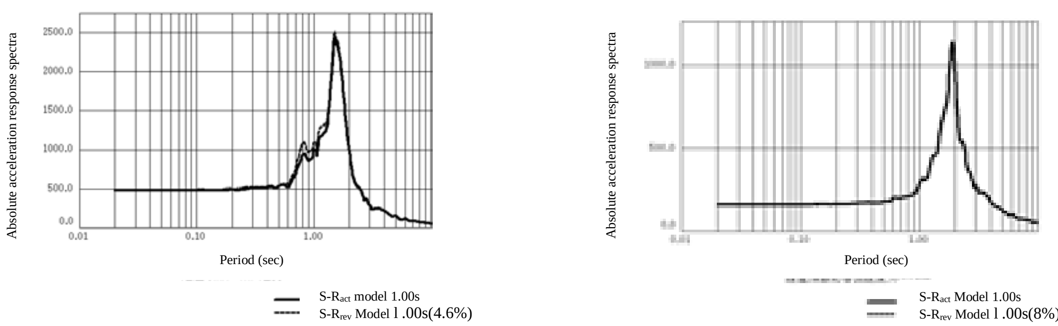
$$h_{rev} = h_0 + h_{eq} \quad (4)$$

where, hrev signifies the objective and suitable inner damping constant of the S-R_{rev} model, h_0 signifies the original inner damping constant, namely 2% (h_0=0.02), and h_{eq} signifies the damping constant as the damping effect due to the dynamic interaction between the building and the soil. As an example of the evaluated value of h_{eq}, in a case with a natural period of T=1.0 sec (in the case of an 18 story building), located on a half-space homogeneous soil structure, G1, and also a two layered soil structure, G2, Fig. 6 shows the result of the response calculated acceleration wave forms at the top of building using S-R_{act} model and S-R_{rev} model, h_{eq}=8.0% in the homogeneous half-space soil layer G1, and h_{eq}=4.6% in the two layered soil model G2. Also, Fig. 7 shows the results of the acceleration response spectra using the S-R_{act} and S-R_{rev} models, respectively. Finally, we performed the same response calculation comparing the response values between the S-R_{act} model and the S-R_{rev} model. Fig. 8 shows the final results of the evaluated h_{eq} values according to the natural period of building which were estimated by equation (3).



(a) In Case of Two Layered Soil Structure Model [G2] (b) In Case of One Layered Soil Structure Model [G1]

Fig. 6 Acceleration Response Wave Form



(a) In Case of Two Layered Soil Structure Model [G2] (b) In Case of One Layered Soil Structure Model [G1]

Fig. 7 Acceleration Response Spectra

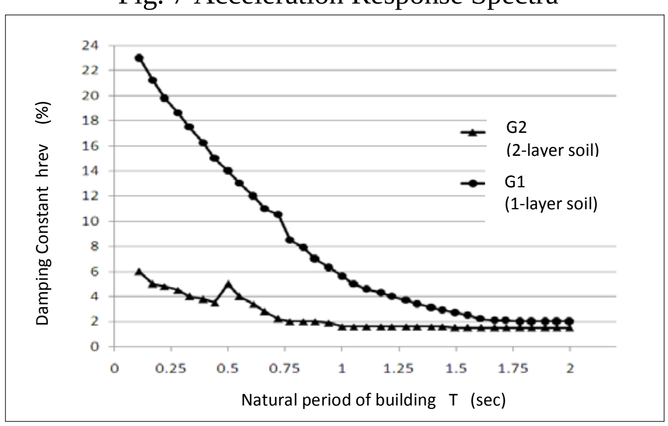


Fig. 8 Result of Damping Effect Evaluated from h_{rev} Due to Soil-Structure Interaction

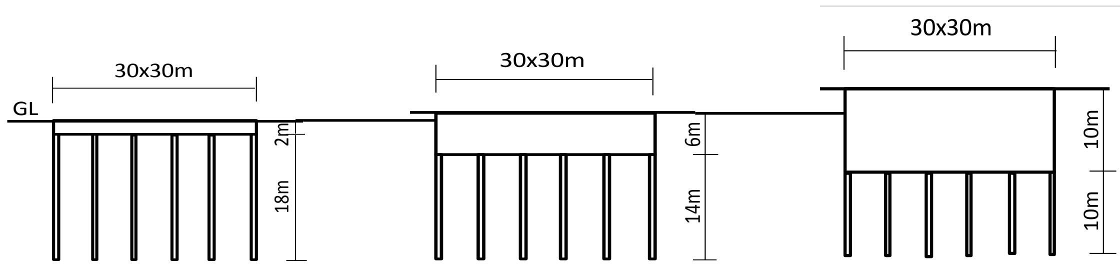
2.5 Results of Damping Effect

In general, the natural period of building related to First Mode is the most important characteristics for the earthquake response of building. The main response characteristics of building vibration were dependent on the first mode natural period and it's possible to estimate the dynamic spring constant of the soil and damping factors. According to Fig. 8, we could understand the clear tendency that the influence of soil manifested more clearly in the shorter natural period of buildings related to the first mode. Namely, it could be understood that the influence of the dynamic interaction manifested more clearly in low rise buildings than in high rise buildings. The converged damping constant value, hrev varies according to the soil structure and, in the case of soft soil condition, the rate of change due to the natural period of the building is even larger. And particularly in the case of short period ranges, namely the low rise building group, the damping effect is very large due to the dynamic interaction with building vibration.

3. Analytical Method in Cases of Pile Foundation

3.1 Setting of Pile Foundation System

We were very interested to investigate the difference in damping effect between direct foundations and pile foundations so we set an analysis model for buildings with pile foundations under the same building conditions used in the building model for direct foundations. The building conditions were the same as the settings indicated in Table 1 and the soil conditions were set with only the two-layer soil model, G2 as indicated in Fig. 1. Also, the foundation types were set to three types, as same as those indicated in Fig. 2; Model R1, Model R2 and Model R3, depending on three groups of buildings, namely low rise, middle rise and high rise. We then set the pile foundations in three types related to foundation types: R1, R2 and R3 used in the building groups. The three types of pile foundation are shown in Fig. 9: Model P1, Model P2, and Model P3. Using the set conditions, we calculated the response of the analysis models for buildings with pile foundations. The assumed analysis cases are shown in Table 5.



(a) Pile Foundation Model for Low Rise Building Group [P1]
(b) Pile Foundation Model for Middle Rise Building Group [P2]
(c) Pile Foundation Model for High Rise Building Group [P3]

Fig. 9 Setting of three types of foundation models for pile systems

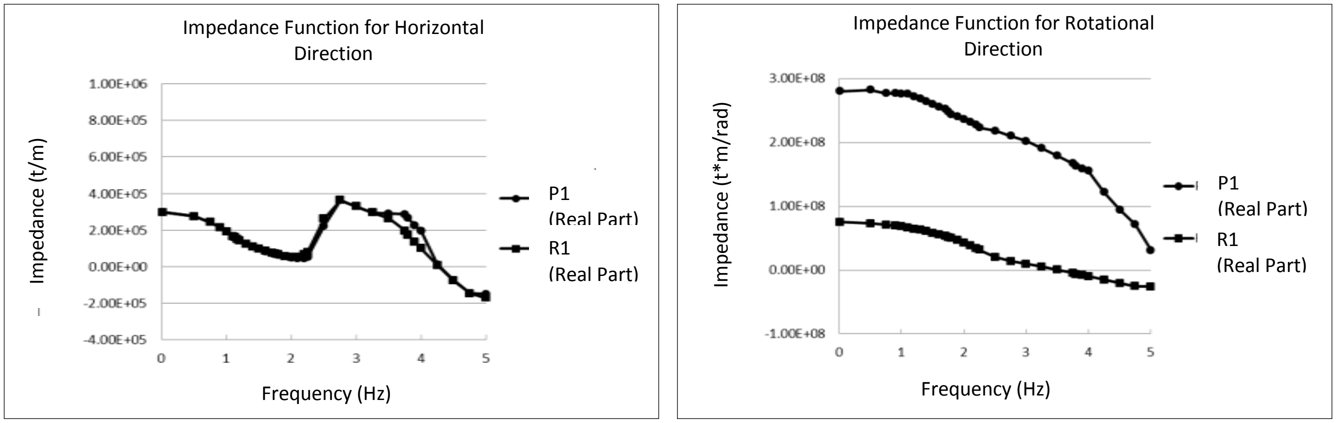
Table 5 Analyzed Cases of Soil and Foundation Combination in Case of Pile Foundation

	Soil Structure	Foundation System
CASE 1P	G2	P1
CASE 2P	G2	P2
CASE 3P	G2	P3

3.2 Calculation of Impedance Function

We calculated the impedance functions in cases of the pile foundations: Model P1, Model P2, and Model P3. The results for impedance for the horizontal and rotational movement of Model P1 in comparison with Model R1 are shown in Fig. 10 as an example.

From Fig. 10, there was no large difference in the horizontal impedance function, namely the horizontal impedance of Model P1 was almost same to the horizontal impedance of Model R1. Whereas, the rotational impedance of Model P1 was much larger than the rotational impedance of Model R1. Such large difference in rotational impedance was caused by the existence of the piles.



(a) Impedance Function for Horizontal Direction (b) Impedance Function for Rotational direction

Fig. 10 Impedance Function for the case of pile foundation

3.3 Calculation of Converged Natural Period

In the same way mentioned in section 2.2, we calculated the converged natural period of the soil-building system including the dynamic interaction by using the S-R Model. The value in fixed foundation model as calculated by equation (3) was set as the initially-assumed natural period of the S-R Model. The initial values of the spring constant and damping constant for the horizontal and rotational movement were evaluated from the impedance function shown in Fig. 10 as the initially assumed natural period of S-R Model. After several steps of iterative calculations changing the assumed natural period of S-R Model, we obtained the converged natural period of building models taking into consideration the soil-building dynamic interaction. The results are indicated in Table 6.

Table 6 Natural Period of S-R_{act} Model and Converged Natural Period of S-R_{rev} Model in Case of Pile Foundation

CASE 1P			CASE 2P			CASE 3P		
N	T	T'	N	T	T'	N	T	T'
2	0.11	0.28	14	0.77	1.02	27	1.50	2.19
3	0.17	0.33	15	0.83	1.07	28	1.55	2.25
4	0.22	0.38	16	0.88	1.12	29	1.61	2.32
5	0.28	0.42	17	0.94	1.18	30	1.67	2.37
6	0.33	0.46	18	1.00	1.23	31	1.72	2.45
7	0.39	0.50	19	1.05	1.29	32	1.78	2.53
8	0.44	0.54	20	1.11	1.35	33	1.83	2.60
9	0.50	0.58	21	1.17	1.41	34	1.89	2.68
10	0.55	0.63	22	1.22	1.46	35	1.94	2.76
11	0.61	0.67	23	1.28	1.53	36	2.00	2.83
12	0.66	0.72	24	1.33	1.59			
13	0.72	0.77	25	1.39	1.66			
			26	1.44	1.74			

N: Number of Building Stories
T: Natural Period of Building in S-R_{act} Model
T': Converged Natural Period of Building in S-R_{rev} Model

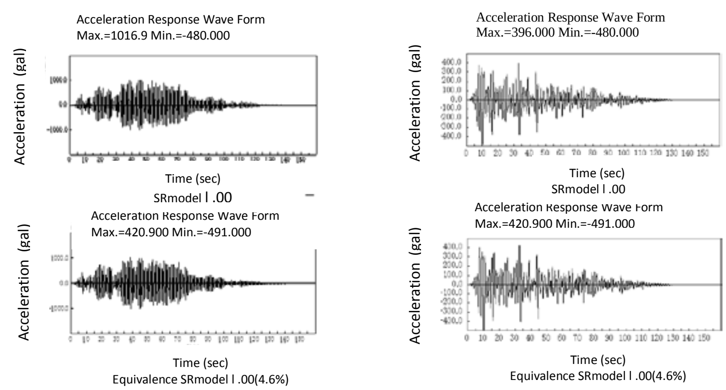
3.4 Seismic Response Analysis

The seismic response analysis was performed in the same manner as the seismic response analysis explained in section 2.3 using two models of the S-R Model, one was the S-R_{act} Model and the other was the S-R_{rev} Model, which are indicated in Fig. 5.

As an example of the results of seismic response analysis, the acceleration response wave forms at the top of the building, the natural period of which was 1.0 sec (As 18 stories building) with a pile foundation, namely the P2 Model, and a direct foundation, namely R2 Model, are shown in Fig. 11 using the S-R_{act} Model and the S-R_{rev} Model, respectively.

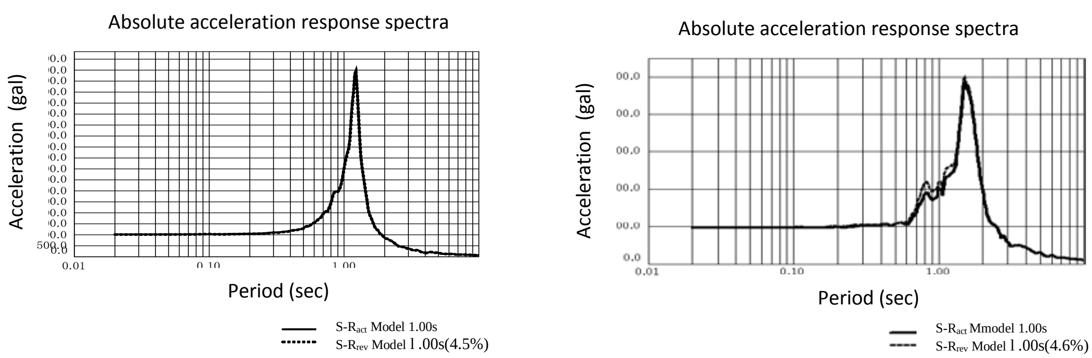
As indicated in Fig. 11, the acceleration response waveforms were very different between the P2 Model and the R2 Model. To obtain the same response between the S-R_{act} Model which was given the original inner damping constant, namely h_0=2.0%, and the S-R_{rev} Model, the equivalent damping constant for the S-R_{rev} Model was set as h_{eq}=4.5% in case of the P2 Model and h_{eq}=4.6% in case of the R2 Model. Also, the acceleration response spectra for the P2 Model and the R2 Model are shown in Fig. 12. In both cases, the results of the acceleration response spectra for the S-R_{act} Model and the S-R_{rev} Model overlapped as shown in Fig. 12, respectively.

As indicated in Fig. 12, the results of response spectra for the S-R_{act} Model and the S-R_{rev} Model almost coincided when, in case of the P2 Model, estimated equivalent damping constant h_{eq}=4.5%, and in the case of the R2 Model, h_{eq}=4.6%.



(a) P2 Model (b) R2 Model

Fig. 11 Acceleration response wave forms for P2 Model and R2 Model
(Upper figure shows the S-R_{act} Model and lower figure shows the S-R_{rev} Model)



(a) P2 Model (b) R2 Model

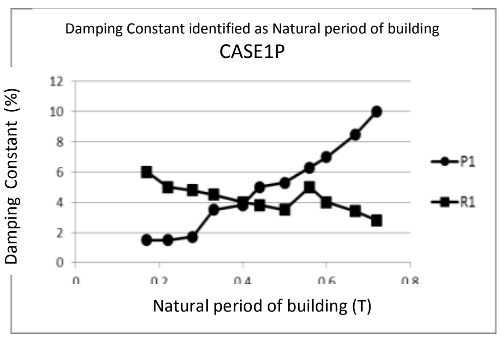
Fig. 12 Acceleration response spectra for P2 Model and R2 Model
(In both figures, the results for S-R_{act} Model and S-R_{rev} Model overlapped)

3.5 Results for Damping Effect

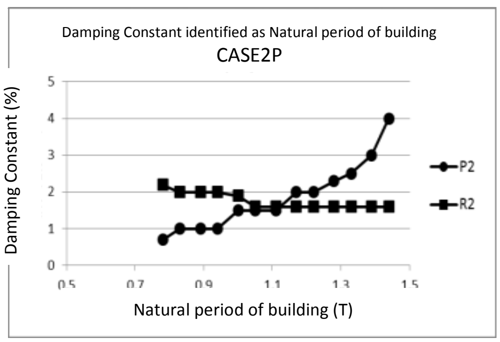
The calculated results of damping effects for three groups of building: low rise, middle rise and high rise, are shown in Fig. 13, for both the P2 Model and R2 Model. The horizontal axis is the natural period of the buildings evaluated by equation (3) assuming a fixed foundation system, and the vertical axis is the equivalent damping constant value using the S-R_{rev} Model, namely h_{eq}. As mentioned in section 2.5, the horizontal axis, the natural period of building, is the natural period in the case of a fixed foundation as calculated by equation (3) according to the number of building stories, and the vertical axis, the equivalent damping constant, means the damping constant which is the equivalent inner damping constant taking into consideration the dynamic interaction between the soil and the building.

From the results shown in Fig. 13, the damping effects, namely the equivalent inner damping constant heq, showed a very large difference between the foundation types: pile foundation and direct foundation. In the case of pile foundations, the equivalent damping constants were larger than the equivalent damping constants in the case of direct foundations. This tendency was much clearer in the high rise building group.

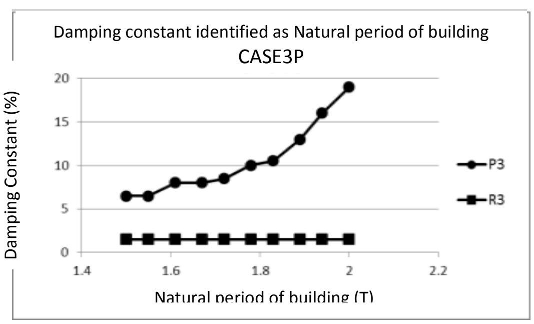
We thought that, in the case of pile foundations, the spring constant for rotational movement was much larger than that of direct foundations, so the equivalent damping constant was evaluated to be much larger than the equivalent damping constant for direct foundations.



(a) In case of low rise building group



(b) In case of middle rise building group



(a) In case of high rise building group

Fig. 13 Results obtained for damping effects due to the dynamic soil-building interaction indicated by the equivalent damping constant h_{eq}.
(Each figure shows the comparison between pile foundation models, P1, P2 and P3 Model and direct foundation models, R1, R2 and R3 Model, respectively)

4. Conclusions

Comparing the maximum response value between the S-R_{act} Model and the S-R_{rev} Model, we obtained the building inner damping constant hrev of the S-R_{rev} Model which has same effect on the building response due to the interaction between soil and building. The result is shown in Fig. 8 where hrev decreases according to the number of building stories, so the higher the building the longer the natural period, the interaction combination effect between the soil and the building is decreases but conversely, the lower the building height and the shorter the natural period. The interaction combination effect increases and hrev is markedly larger.

The results show that for pile foundations, the P1, P2 and P3 Models show a larger damping constant heq, namely they show a larger damping effect due to the dynamic interaction between the soil and the building, namely dispersed damping effects largely appeared in case of pile foundations. Also, this tendency was clear in case of the high rise building group as indicated in Fig. 13, and the rotational movement impedance was evaluated to be larger in the case of a pile foundation, and as also indicated in Table 6, the converged natural period was did not differ greatly between the natural period evaluated under fixed foundation conditions and pile foundation, so, we thought that pile foundations have much stronger resistance to movement and the equivalent damping constant was evaluated as having larger damping effects.

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