PROPOSAL OF NEW FOUNDATION CONSTRUCTION WORKS WITH HIGH DAMPING AND MITIGATION PERFORMANCE; PART 2 EARTHQUAKE OBSERVATION OF BLOCKS AND SEISMIC RESPONSE PREDICTION OF FULL-SCALED FOUNDATIONS

Y. Shimomura[1], Y. Ikeda [2], M. Kawamura [3], N. Sako[4] and S. Ishimaru[5]

[1] *Professor, Dept. of Construction, Nihon University Junior College, Japan*
[2] *Manager, Taisei Corporation, Japan*
[3] *Professor, College of Industrial Technology, Nihon University, Japan*
[4] *Assistant Professor, Dept. of Construction, Nihon University Junior College, Japan*
[5] *Professor, College of Science and Technology, Nihon University, Japan*
Email: shimo@arch.jcn.nihon-u.ac.jp

ABSTRACT :

After the forced vibration tests, we have continued seismic observations at the experiment site (two types of foundation blocks, that is CF and IF, and their surrounding grounds) to confirm the effectiveness of the proposed foundation procedure during earthquakes. The CF was constructed by a conventional construction method and the IF applied the proposed improved foundation technique. Previously we have obtained many earthquake records, i.e., The Mid Niigata prefecture Earthquake in 2004, The Northwest Chiba prefecture Earthquake in 2005 and so forth. The Northwest Chiba prefecture Earthquake provided the largest acceleration observation record in the last ten years at the experiment site. The evaluation of the spectral intensity of the observation records indicated that the proposed foundation technique would effectively reduce the severe damage of earthquake destructivity. However, the efficient results by the seismic response were not shown in comparison with forced vibration tests because the size of the foundation block was too small. Therefore, the seismic response analysis of a full-scaled structure that installs the damping material into trenches dug along the foundation was carried out, and the effectiveness of the proposed damping material on seismic response mitigation of the structure was demonstrated.

KEYWORDS: Damping performance, damping mixtures, foundation blocks, earthquake observation, seismic response prediction

1. INTRODUCTION

In the accompanying paper (Part 1), a new foundation work with damping and mitigation performance was proposed and the validity of the proposed foundation work was shown through forced vibration tests and simulation analyses. After the forced vibration tests, we have continued seismic observations at the experimental site to confirm the effectiveness of the proposed foundation procedure during earthquakes. In both experiments and observations, we dealt with two types of foundation work (CF and IF) and their surrounding soil condition. The CF was constructed by a conventional construction method and the IF applied the proposed improved foundation technique. We have already obtained many earthquake records, i.e., The Mid Niigata prefecture Earthquake in 2004, The Northwest Chiba prefecture Earthquake in 2005 and so forth. The Mid Niigata prefecture Earthquake struck Niigata Prefecture on the evening of October 23rd, 2004 and was the most significant earthquake to affect Japan since The Hyougoken-Nambu Earthquake in 1995. The Northwest Chiba prefecture Earthquake provided the largest acceleration observation record in the last ten years at the experiment site.

In order to confirm the attenuation performance of the proposed damping material for earthquakes, analyses of earthquake observation records and their simulation analysis were conducted. In the simulation analyses, 2-dimensional finite elements method and hybrid approach, which treated the CF, the IF, and their adjacent soil region as 3-dimensional finite elements and the soil free field region as thin layer approach, were adopted. For modeling of the simulation analysis, two foundations, the soil region surrounding the foundations, and ground points where seismographs were installed, were all taken into consideration.

The attenuation performance of our proposed damping composite is confirmed by the seismic observation records and simulation analyses. However, the efficient results by the seismic response were not shown compared with the forced vibration tests because the size of the foundation block was too small. Therefore, to investigate the effectiveness of the proposed damping mixture on the seismic response mitigation of the structure, the seismic response analysis of a full-scaled structure that installs the damping mixture into trenches dug along the foundation was carried out.

2. SEISMOGRAPH INSTALLATION AT EXPERIMENTAL SITE

Figure 1 shows the layout of our experimental site. As shown in Figure 2, seismographs have been installed in the pit basement of an experimental building, the shaking table and basement of a base-isolation structure and under the ground (Ishimaru et al. 2004). The shear wave velocity at G.L.-38m beneath the base-isolation structure has exceeded 400 m/s. Therefore it was recognized that this point is as the engineering bedrock. Here, we refer to the engineering bedrock point as S4. At the experiment site, we have installed eight seismographs. Two seismographs have been mounted on the east and west sides on the surface of each foundation. Three seismographs near both foundations are located at G.L.-1.0m. Each seismograph, shown in Figure 1, is located at the midpoint of the CF and IF (S1); 3m towards the east from the center of the IF (S2); and 6m to the north from the center of the CF (S3). Another seismograph is installed at G.L.-22m under the S3.

3. ANALYSIS OF OBSERVATION RECORDS

3.1. Time Histories

After the final experiment, we have continued earthquake observations at the experimental site. We previously obtained many earthquake records including The Mid Niigata prefecture Earthquake in 2004 and The Northwest Chiba prefecture Earthquake in 2005. The Mid Niigata prefecture Earthquake struck Niigata prefecture on the evening of October 23rd, 2004. It was M_{JMA} 6.8 earthquake. This was the most significant earthquake to cause heavy damage in Japan since The Hyougoken-Nambu Earthquake in 1995. We obtained records of the main shock wave of the earthquake and its aftershocks. The epicentral distance from the epicenter to the experimental site at Funabashi city in Chiba prefecture was about 230km. The Northwest Chiba prefecture Earthquake hit the metropolitan area on the evening of July 23rd, 2005, and was an earthquake which exposed the inability of urban sites to withstand earthquake disaster. In addition, it was the earthquake which had the largest acceleration observation recorded in the last ten years at our Funabashi campus.

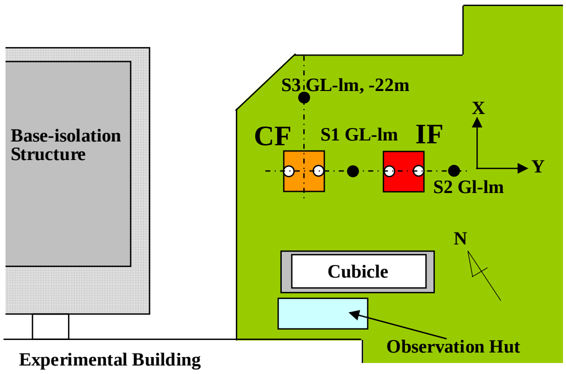


Figure 1 Schematic view of the test site

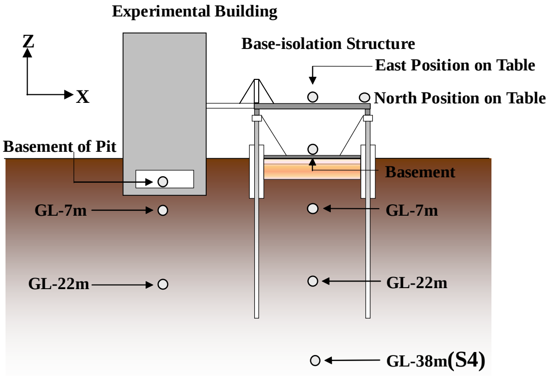


Figure 2 Seismograph installation

As an example illustrating the acceleration time history, Figure 3 shows the principal motion parts of the main shock records of The Northwest Chiba prefecture Earthquake at the two foundations, and the soil region near the foundations illustrated in Figure 1. The catalog, the two earthquake records, and their aftershocks, is shown in Table 1. Table 2 shows the peak accelerations (PA) and the spectral intensities (SI) (after Housner, 1952), which are estimated by the records observed from both foundations. The sway component represents an average transverse acceleration of two observation points at each foundation and the pseudo rocking component is a rotational acceleration calculated by differences between two vertical records. In terms of the SI that represents an input earthquake energy considering period characteristics of structures, all the SI values of the IF are smaller than those of the CF. In particular, the rocking components of the IF become considerably smaller than the sway components of the IF. This indicates that the proposed damping mixture positively affects the mitigation performance of foundations against earthquake destructivity.

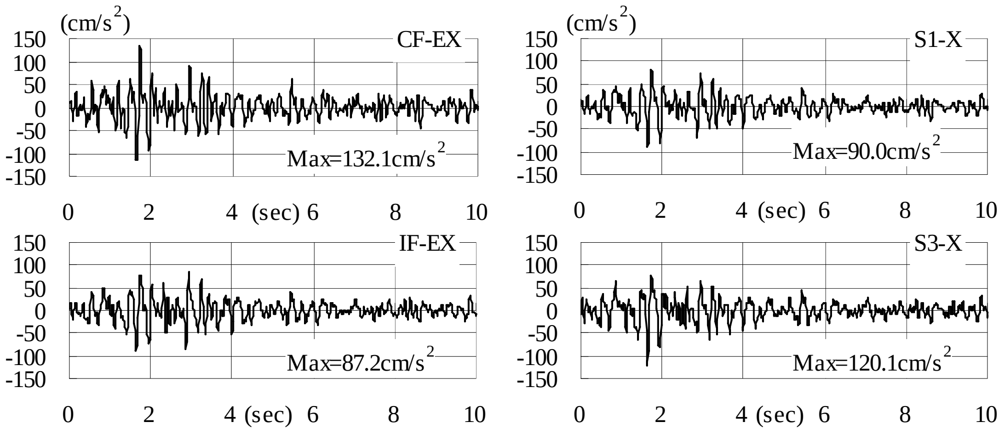


Figure 3 Examples of acceleration time history records (The Northwest Chiba prefecture Earthquake)

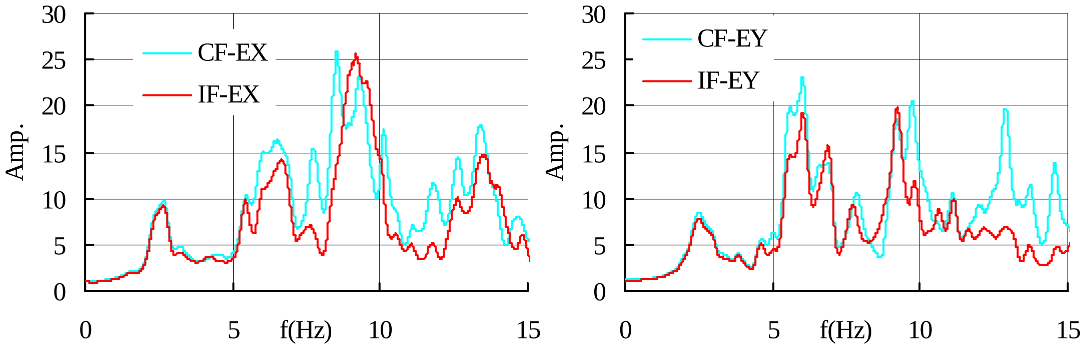
Table 1 Catalog of earthquake records.

No.	Occurrence time (Y/M/D/H/m)	Epicenter	Depth (km)	Magnitude	Epicentral distance (km)	I_{JMA}
1^{*A}	2004/10/23/17/56	Chuestu of Niigata pref.	13	6.8	220	III
2^{*B}	2004/10/27/10/41		12	6.1	200	II
3^{*C}	2005/07/23/16/35	Northwest of Chiba pref.	73	6.0	17	IV
4^{*D}	2005/07/23/16/42		69	4.2	13	I

^{*A}: The main shock of The Mid Niigata prefecture Earthquake
^{*B}: An aftershock of The Mid Niigata prefecture Earthquake
$^{*C:}$ The main shock of The Northwest Chiba prefecture Earthquake
^{*D}: An aftershock of The Northwest Chiba prefecture Earthquake

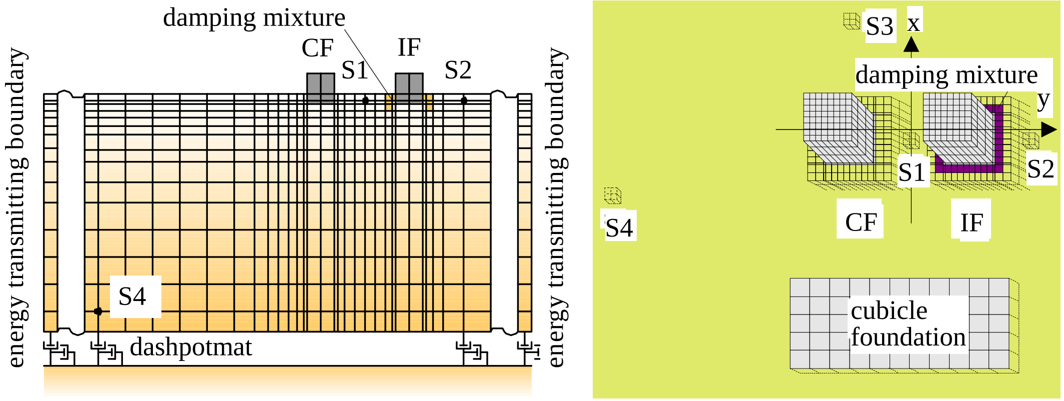
Table 2 Peak accelerations and spectrum intensities

Earthquake	Component	Sway			Sway			Rocking		
	Direction	X			Y			Y		
	Foundation	CF	IF	IF/CF	CF	IF	IF/CF	CF	IF	IF/CF
No.1	PA(cm/s^2)	28.53	24.61	0.86	33.29	27.05	0.81	3.78	1.90	0.50
	SI(cm/s)	3.73	3.53	0.95	3.64	3.47	0.95	0.27	0.14	0.53
No.2	PA(cm/s^2)	10.99	10.62	0.97	7.53	6.93	0.92	0.83	0.64	0.77
	SI(cm/s)	1.60	1.53	0.95	1.56	1.49	0.96	0.08	0.04	0.50
No.3	PA(cm/s^2)	130.41	88.83	0.68	97.57	84.61	0.87	11.59	5.55	0.48
	SI(cm/s)	1.60	1.53	0.95	1.56	1.49	0.96	0.08	0.04	0.50
No.4	PA(cm/s^2)	14.48	12.71	0.88	11.10	10.02	0.90	2.07	1.25	0.60
	SI(cm/s)	0.73	0.61	0.84	0.56	0.50	0.90	0.09	0.05	0.62



(a) Transfer functions for x direction (b) Transfer functions for y direction

Figure 4 Transfer functions of CF and IF to S4



(a) 2-dimensional model (b) 3-dimensional model

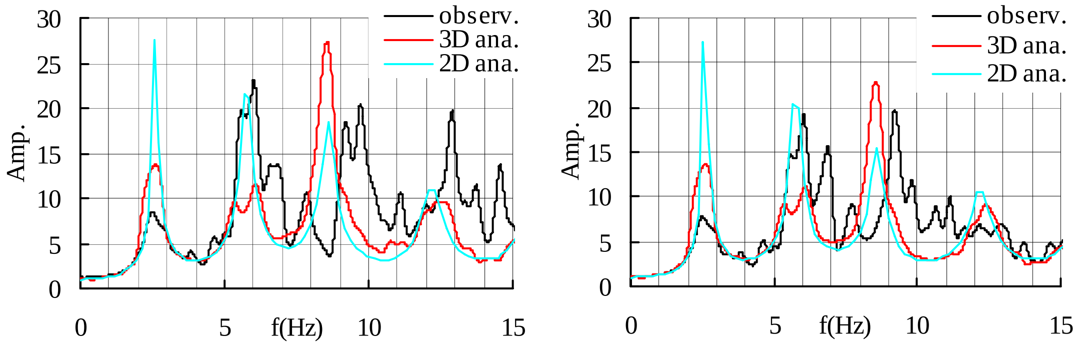
Figure 5 Two models for simulation analyses of earthquake response of foundation blocks

Table 3 Properties of numerical analysis

Depth (m)	V_s (m/s)	ρ (t/m^3)	Poisson’s ratio	Damping ratio
1.0	90	1.4	0.311	0.03
2.7	90	1.4	0.311	0.03
5.4	150	1.6	0.451	0.03
10.6	280	1.7	0.372	0.02
14.7	280	1.7	0.478	0.02
21.7	350	1.7	0.465	0.02
27.8	380	1.8	0.461	0.02
38.0	450	2.0	0.466	0.02
45.2	420	2.0	0.461	0.02
Material				
Foundation blocks	-	2.4	0.20	0.00
Leveling concrete	-	2.4	0.20	0.00
Damping mixture	163	1.68	0.35	0.20

3.2. Transfer Functions

Figure 4 displays transfer functions of the CF and the IF to the S4. These transfer functions are calculated by the main shock of The Mid Niigata prefecture Earthquake. Peak frequencies that can be seen in the transfer functions for x and y directions are the dominant frequencies of the soil region (from the first to the fourth modes), which are above the G.L.-38m. For x direction, the transfer functions of both foundations are approximately the same. Conversely, for y direction, the transfer function of the IF is smaller than that of the CF in the frequency range of 9.0Hz and above.



(a) Transfer functions of CF (b) Transfer functions of IF

Figure 6 Comparison of transfer functions of CF and IF of observations and analyses for y direction.

4. SIMULATION ANALYSIS OF EARTHQUAKE OBSERVATION RECORDS

4.1. Simulation Analysis Models

To grasp the fundamental vibration characteristics of earthquake records of the CF, the IF, and the soil region surrounding both foundations, simulation analyses employing the 2-dimensional finite element approach have been carried out. In the 2-dimensional analysis modeling, we have taken into account the y component that is equal to a parallel direction of the CF and the IF. The S1 and S2 in the soil region near the two foundations and the S4, which locates G.L.-38m beneath the base-isolation structure, are also modeled. The 2-dimensional model is shown in Figure 5(a). The transfer functions of the two foundations and ground points to the steady state harmonic incident wave defined at the bottom of the dashpot mat underneath the analysis model are also evaluated. Table 3 indicates the shear wave velocities of each stratum of the model.

The 3-dimensional analysis using the hybrid model, which has already been utilized for simulation analysis of the forced vibration tests, is also applicable in the simulation of earthquake responses (Shimomura et al., 2005). Figure 5(b) shows the 3-dimensional analysis model. The CF and IF, the S1, S2 and S3 in the soil region near the foundations, the basement of the cubicle, and the S4 are considered the same as the simulation of forced vibration tests. We calculate transfer functions of the foundations or the soil points to the S4 to compare with observation records as well as the 2-dimensional analyses. In the 3-dimensional analysis, to obtain appropriate results, we have taken into account the responses of y direction that are induced not only by the y component but also by the x component of earthquake input motions (Ikeda et al., 2004).

4.2. Comparison with Observation Records and Analysis Results

Figure 6 illustrates the transfer functions of both foundations to the S4 calculated by the main shock of The Mid Niigata prefecture Earthquake. The 2-dimensional analyses and 3-dimensional analyses estimate the peak frequencies of the third mode lower than the observation. The amplification of the first mode of the 3-dimensional analysis agrees well with the observation, comparing with that of the 2-dimensional analysis. It was found that the third mode's amplification of the IF of the observation is smaller than that of the CF. From the results of the 3-dimensional analyses, the same trend can be seen at the first coupled mode of the foundations and the soil region. This might be expected because of the attenuation performance of the damping mixture. As a result, the transfer functions of both analyses correspond approximately with the observation. In particular, it has been confirmed that the 3-dimensional analysis provides more detailed features of the earthquake records than the 2-dimensional analysis, except for the second dominant frequency range of the ground.

5. PREDICTION ANALYSIS OF SEISMIC RESPONSE OF FULL-SCALED STRUCTURE

5.1. Modeling of Structure and Soil

The postulated frame structure is an office building that has six floors including one underground floor, and its configuration of foundation is 25m square. Height of each floor level is 3m and that of the underground level is 5m, as shown in Figure 7. First, a seismic analysis model of the frame structure was developed and an eigenvalue analysis, in which the upper surface of the foundation was fixed, was carried out. Then the static push-over analysis was executed to estimate the shearing section area and the geometric moment of inertia on each floor by the relationship between the obtained deformations and the given loads. And a stick model that concentrated mass at each floor level was developed. In order to meet with the first mode of the frame model, section properties of the stick model were justified. It is assumed that the underground part is rigid body and the total mass of this part is uniformly distributed. Properties of superstructure are shown in Table 4. The foundation and soil undergoing the above superstructure are modeled by an axisymmetric finite element model. An equivalent radius of the foundation is 14.015m and the soil that has surface layer of 10m is two-layered model. Shear wave velocities of the surface and supported soils are 100m/s and 200m/s, respectively.

5.2.Analysis Cases

In this simulation analysis, we focus on the soil conditions around the foundation. The first model that has the above soil conditions is a basic one (Case A). The second model that takes into account soil improvement underneath the foundation is referred to as Case B. The third model has a 4m deep trench that is filled with the proposed damping mixture of asphalt with crushed stones and rubber chips is referred to as Case C. Latest, Case D model has a trench twice as deep as Case C, and its trench is filled with the proposed mixture. The four models are shown in Table 4, and the material parameters used in this analysis defined by the material tests are displayed in Table 5.

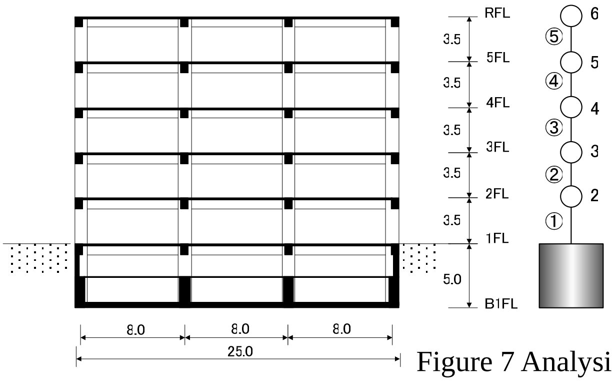
5.3.Impedance Functions and Equivalent Damping Constants

The comparison of each case for sway, rocking, and coupling components of impedance functions and equivalent damping constants was carried out. Figures 8 and 9 show real and imaginary parts of sway and rocking impedance functions and equivalent damping constants. The horizontal scale of each figure shows a dimensionless frequency of $a_0=\omega b/V_s$, where ω is the circular frequency, b is the half width of the square foundation (12.5m), and V_s is the shear wave velocity of the supported soil (200m/s). Longitudinal scale is dimensionless stiffness of the ratio of the impedance functions to the product of V_s and b. It is found that static stiffness of Cases C and D is larger than that of Cases A and B because the static stiffness is affected by the shear wave velocities of the soil underneath or around the foundation. Since conditions of the foundation's edges have an effect on the rocking impedance functions, this tendency can be expressed in the rocking component more strongly than sway one. Also, because real parts of the impedance functions of Cases C and D are influenced strongly by the additional mass, the sway and rocking components fall dramatically from $a_0=0.7$ and $a_0=1.5$, respectively.

Imaginary parts of the sway and rocking impedance functions calculated using Cases C and D are significantly larger than those of Cases A and B. Therefore, it has been confirmed that the attenuation performance of the proposed damping mixture installed around the foundation has appeared effective. The equivalent damping constants estimated by the sway and rocking impedance functions of Cases C and D are also larger than those of Cases A and B. In particular, the rocking component of the equivalent damping constant shows this tendency more remarkably than the sway one. The trend, mentioned above, when the proposed damping mixture installed around the foundation has an effect on the mitigation of rotational response, agrees well with results obtained from the earthquake observation records.

5.4.Seismic Analysis

As for the results of the structure seismic response, Figure 10 shows translation amplification ratios of 2FL, 4FL, and RFL to the surface of the free field soil U_0. It should be noted that, the amplification ratio in Cases C and D, in which the damping mixture was set around the foundation, decreased compared with Cases A and B. Decrease in the amplification ratio from about 10% to 30% indicates that the proposed damping material plays an important role in mitigation of seismic response on structures.



Node	Element	Height (m)	Mass (ton)	Shearing section area	Moment of inertia (m^4)
6		22.5	890		
	⑤			0.3394	1280
5		19	890		
	④			0.3394	1280
4		15.5	890		
	③			0.3394	1280
3		12	890		
	②			0.384	1280
2		8.5	890		
	①			0.384	1280
Foundation		-	2920		

Figure 7 Analysis model (superstructure)

Table 4 Analysis cases (soil and foundation)

Case	a	b	c	d	e
A	I	II	II	II	II
B	I	II	III	II	II
C	I	II	III	IV	IV
D	I	II	III	IV	IV

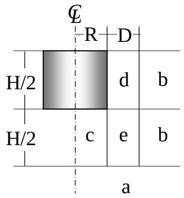


Table 5 Properties of soil and other materials

		V_s (m/s)	ρ (ton/m^3)	ν	h
I	Supported soil	200	1.8	0.45	0.02
II	Surface layered	100	1.6	0.45	0.02
III	Improved soil	130	1.7	0.45	0.02
IV	Damping mixture	165	1.7	0.35	0.2

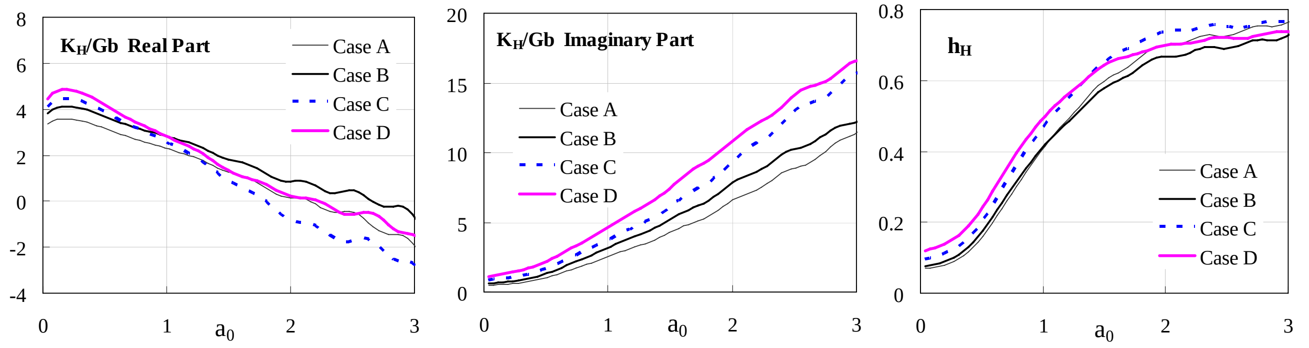


Figure 8 Sway impedance functions

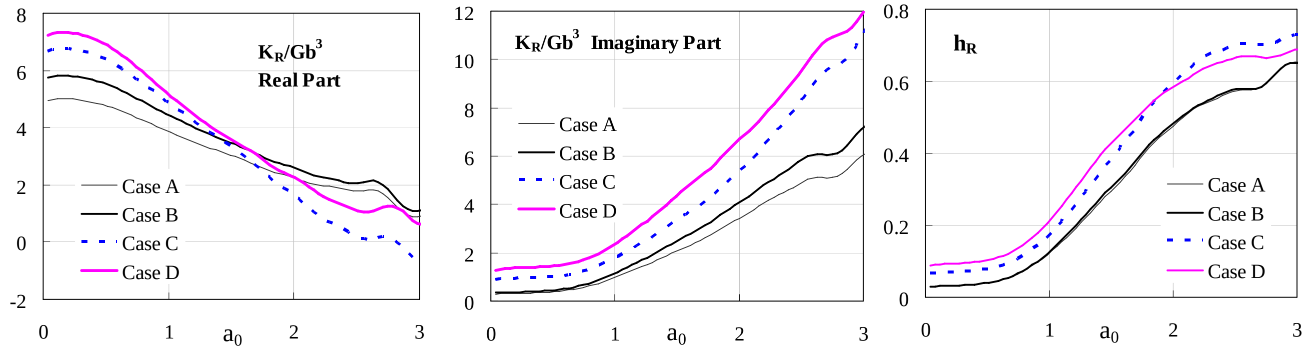


Figure 9 Rocking impedance functions

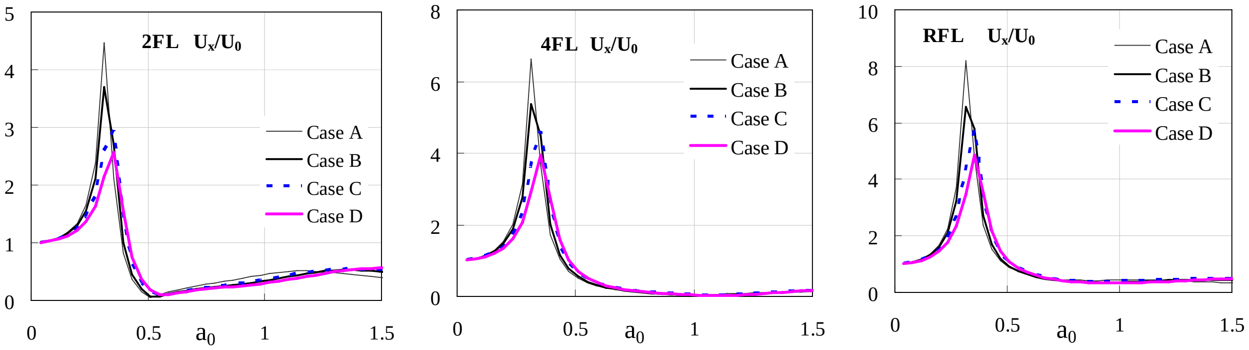


Figure 10 Transfer functions against free field soil

6. CONCLUSIONS

After the forced vibration tests, we have continued seismic observations at the experimental site to confirm the effectiveness of the proposed foundation procedure during earthquakes. We have already obtained many earthquake records, i.e., The Mid Niigata prefecture Earthquake in 2004 and so on. The evaluation of the spectral intensity of the observation records indicated that the proposed foundation technique would have effectively reduced the severe damage of the earthquake’s destructivity. The hybrid approach, used here, was tested as a viable method to conduct the simulation analyses of not only the forced vibration tests but also the earthquake response. It was found that the attenuation ability of the proposed damping material during earthquakes is less than at forced vibration tests. This is the reason why the earthquake input motion from the side surfaces of the foundations tested was insufficient due to the small size of the foundation block. To investigate the effectiveness of the proposed damping mixture on seismic response mitigation of the structure, the seismic response analysis of a full-scaled structure that backfills the damping material into trenches dug along the foundation was carried out. As an example of applying the proposed damping mixture to a full-scaled structure, seismic response analyses were carried out. Response mitigation effect derived by pertinently installing the proposed damping material around the foundation can be confirmed not only experimentally but also analytically.

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