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EFFECT OF SOIL-STRUCTURE INTERACTION OF LOW- AND MIDDLE-RISE BUILDINGS BASED ON STRONG MOTION DATA

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Abstract

The Building Research Institute (BRI) of Japan is a national institute engaged in research and development in the fields of architecture, building engineering, and urban planning. The BRI operates the strong motion network that covers buildings in major cities across Japan, as part of its research activities. Eighty-five strong motion stations are currently in operation.

The dynamic soil-structure interaction (SSI) is one of key issues, which remain to be fully discussed, on the seismic safety of building structures. The complicated SSI phenomena are likely to be affected by the factors such as building structures, foundation types and soil conditions. Therefore, an observation of the actual SSI phenomena is useful in investigating their effects on the seismic safety. From a view of contribution to the SSI study, sensors have been installed in one third of the buildings in the BRI strong motion network both in doors and on the ground.

In order to investigate actual SSI effects, twelve buildings having sensors both in doors and on the ground were selected from among those in the BRI strong motion network. The buildings vary in the number of stories, foundation type and ground condition. Furthermore, five earthquakes including the 2011 Tohoku Earthquake were chosen for obtaining strong motion data to be analyzed.

First, peak accelerations were examined in order to discuss the amplification level of the earthquake motions across the area from the ground to the building top. The peak accelerations at the building foundation were generally reduced compared with those on the ground, and then were amplified by the building structures. The peak accelerations at the building top were 2 to 5 times higher than that at the building foundation.

Second, the dynamic characteristics of the swaying-building and building systems were minutely investigated. The natural period of the swaying-building system was longer than that of the building system in every case. A difference in natural period between the swaying-building and building systems was significant in the low-rise buildings. A difference in damping ratio between the swaying-building and building systems was also large in the low-rise buildings. An increase in natural period caused by the Tohoku Earthquake was observed in many of the middle-rise buildings.

Finally, the seismic input loss was discussed using the Fourier spectrum ratios between acceleration data on the ground and at the building foundation. Although the spectrum ratios of all the cases decreased in the short period range, their shapes were different depending on the building.

The paper tried to clarify variation in SSI effect considering their relevance to various parameters, such as the building properties, foundation type and ground condition. We need a further investigation in order to discuss the contribution of those parameters to the seismic response of buildings.

Keywords: Soil-structure interaction, 2011 Tohoku Earthquake, Strong motion data

1. Introduction

The Building Research Institute (BRI) of Japan is a national institute engaged in research and development in the fields of architecture, building engineering, and urban planning. The BRI operates the strong motion network that covers buildings in major cities across Japan, as part of its research activities.

The dynamic soil-structure interaction (SSI) is one of key issues, which remain to be fully discussed, on the seismic safety of building structures. The complicated SSI phenomena are likely to be affected by the factors such as the building structure, foundation type and soil condition. Therefore, an observation of the actual phenomena is useful in investigating the SSI effects. From a view of contribution to the SSI study, sensors have been installed in one third of the buildings in the BRI strong motion network both in doors and on the ground.

On 11 March, 2011, an enormous earthquake with a moment magnitude (Mw) of 9.0 occurred off the Pacific coast of northeast Japan. The earthquake, known as the Great East Japan Earthquake (hereafter, simply referred to as the Tohoku Earthquake), caused a monstrous tsunami and massive damage to eastern Japan. Seventy-nine stations in the BRI strong motion network were running at the time of the earthquake. Among them, 61 stations were triggered [1].

We select buildings having a sensor on the ground in the high seismic intensity area at the time of the 2011 Tohoku Earthquake to discuss the SSI effects under the severe shaking condition. Then a change in the dynamic characteristics of the buildings is examined considering the SSI effects. Moreover, the seismic input loss from the buildings is investigated through the Fourier spectrum analysis.

2. Target Buildings and Earthquakes

Twelve low- and middle-rise buildings are selected for the study as listed in Table 1. The locations of the buildings are plotted in Fig. 1. The buildings are located in and around Tokyo, the capital of Japan. They have the reinforced concrete (RC) or steel framed reinforced concrete (SRC) structures with three to nine stories. The buildings B, D, F, G and I to L have a basement floor(s). The buildings from B to F, H and J have pile foundations. The ground conditions of the sites of buildings C, E and F are soft according to the Building Standard Law of Japan. In this paper, the long and short side directions of each building are referred to as X- and Y-directions, respectively.

Table 1 – Target buildings for analysis

Code	Location	Structure	Floors	Basement Floors	Foundation	Soil type
A	Kodaira City	RC	3		Mat	Medium
B	Shibuya Ward	RC	4	1	Pile	Medium
C	Miyashiro Town	RC	6		Pile	Soft
D	Yachiyo City	RC	6	1	Pile	Medium
E	Minato Ward	SRC	7		Pile	Soft
F	Misato City	SRC	7	1	Pile	Soft
G	Tsukuba City	SRC	7	1	Mat	Medium
H	Funabashi City	RC	8		Pile	Medium
I	Tsukuba City	SRC	8	1	Mat	Medium
J	Toda City	SRC	8	1	Pile	Medium
K	Chiba City	SRC	8	1	Mat	Medium
L	Bunkyo Ward	SRC	9	2	Mat	Medium

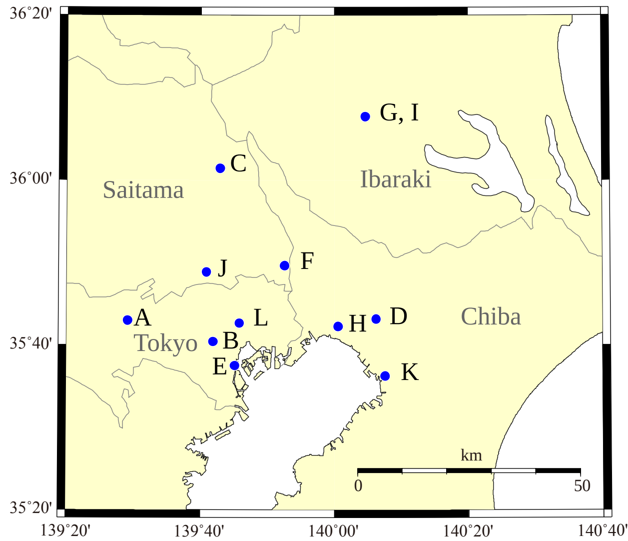

Fig. 1 – Locations of target buildings

In order to discuss a change in dynamic characteristics including the soil-structure interaction effects, five earthquakes are chosen as shown in Table 2. The earthquake EQ3 is the mainshock of the Tohoku Earthquake of March 11, 2011. The earthquakes EQ1 and EQ2 are selected to obtain data on strong motion with moderate seismic intensity before the Tohoku Earthquake. The earthquakes EQ4 and EQ5 are large aftershocks of the Tohoku Earthquake. PGA in Table 2 indicates peak ground accelerations at the site of the building L, which is close to the centre of Tokyo. The peak ground accelerations of EQ1, EQ2, EQ4 and EQ5 are 1/20 to 1/5 of that of the Tohoku Earthquake.

The locations of the epicentres of the target earthquakes are plotted in Fig 2. The target buildings are enclosed in the green box in Fig. 2. The closest earthquake to the sites of these buildings is EQ5 that is 105 km away from the buildings G and I. The buildings are at distances of more than 300 km from the epicentres of other earthquakes.

Table 2 – Target earthquakes for analysis

No.	Date time	M*	Depth (km)	Location	PGA** (cm/s^2)
EQ1	2008/07/24 00:26	6.8	108	N Coast, Iwate Pref.	10
EQ2	2009/08/09 19:55	6.8	333	S Off Tokaido	46
EQ3	2011/03/11 14:46	9.0	24	Off Sanriku	218
EQ4	2011/04/07 23:32	7.2	66	Off Miyagi Pref.	23
EQ5	2011/04/11 17:16	7.0	6	Hama-dori, Fukushima Pref.	32

*: Moment magnitude for EQ3, Japan Meteorological Agency (JMA) magnitude for others.

**: Peak ground acceleration at the site of the building L.

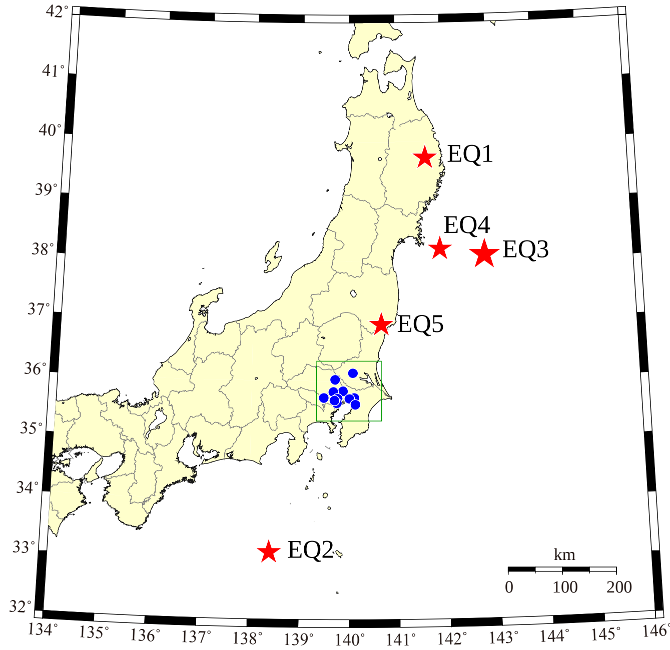

Fig. 2 – Locations of epicentres (buildings are situated in the green rectangle)

3. Analytical Method

The soil-structure interaction is often discussed using a simple model having springs and dampers of swaying and rocking as shown on the left side of Fig. 3. In this model, five measuring points are necessary to separate each movement from the strong motion data. Each strong motion station listed in Table 1 has an acceleration sensor on the ground, with no sensors that make it possible to estimate rocking movement. Therefore, we adopt a swaying model that has a horizontal spring and a damper between the foundation and ground as indicated on the right side of Fig. 3. The bottommost and topmost sensors are adopted as the sensors at the building foundation and top of each building.

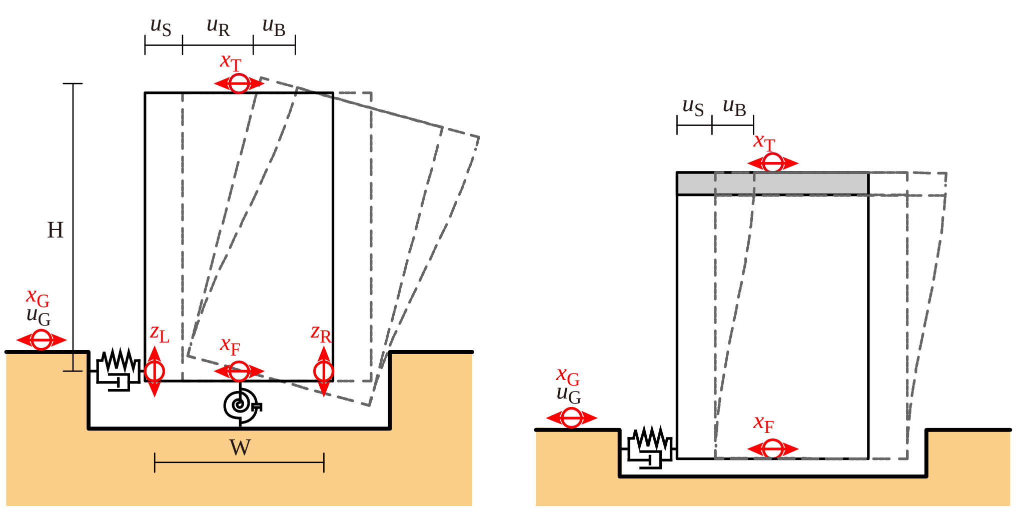

Fig. 3 – SSI models

Using the swaying model, two input-output systems are assumed as described in Table 3 [2]. With the assumption that movements on the ground (x_G) and at the building top (x_T) are the input and output, respectively, the system indicates characteristics including the effect of the swaying in addition to the building deformation. The system from the building foundation (x_F) to the building top (x_T) reflects dynamic characteristics of the building. The two systems (x_G to x_T and x_F to x_T) are hereafter referred to as the swaying-building (SB) and building (B) systems, respectively.

Table 3 – Input-output systems to be identified [2]

System	Input	Output	Parameter
Swaying-building (SB)	u_G (x_G)	$u_G + u_S + u_B$ (x_T)	T_{SB}, h_{SB}
Building (B)	$u_G + u_S$ (x_F)	$u_G + u_S + u_B$ (x_T)	T_B, h_B

The natural period and damping ratio are estimated with a single-degree-of-freedom (SDOF) system assumed for each of the input-output systems. The system identification is made by the parameter optimization technique. Since only two parameters, the natural period and damping ratio, are used to express the dynamic characteristics of the SDOF system, the grid search method is adopted as an identification algorithm. The fitness of a search point is evaluated by means of the integral square difference between the observed and simulated response accelerations [3, 4].

4. Peak Accelerations

The amplification level of earthquake motions is frequently discussed through the comparison between peak acceleration values at measuring points. This chapter investigates peak accelerations and a difference among them from this point of view.

Fig. 4 (a) plots peak accelerations on the ground (G), at the building foundation (F) and at the building top (T) in the X-direction of each building. Square, triangle, circle, inverted triangle and diamond symbols represent the values of EQ1, EQ2, EQ3, EQ4 and EQ5, respectively. Red, blue and green symbols correspond to the values on the ground, at the building foundation and at the building top, respectively. Letter codes of the buildings having a basement floor(s), pile foundation and soft ground condition are overprinted by squares (□), diamonds (◇) and underscores ( ), respectively. The peak accelerations on the ground during the Tohoku Earthquake (EQ3) exceeded 100 cm/s^2 at every strong motion station. The peak accelerations at the building top during the Tohoku Earthquake widely varied between 129 cm/s^2 and 585 cm/s^2.

Fig. 4 (b) plots ratios of peak accelerations between the ground and building foundation (F/G), between the ground and building top (T/G), and between the building foundation and building top (T/F). Red, blue and green symbols indicate the ratios of F/G, T/G and T/F, respectively. The ratio F/G, which is a difference in peak acceleration between the ground and foundation, has values between 0.3 and 1.0. The ratio of F/G widely varies among the buildings, but the possible causes of the differences are not clear. The peak acceleration ratios T/G, which represent the amplification level across the area from the ground to building top, are varied between 1.0 and 4.0. Although the ratios of low-rise buildings (A to E) show small values (< 1.5), the ratios of middle-rise buildings are larger than 2.0. The peak acceleration ratio T/F, which characterises the amplification level according to the building structure, is dispersed between 2.0 and 5.0 except the buildings A, B and E.

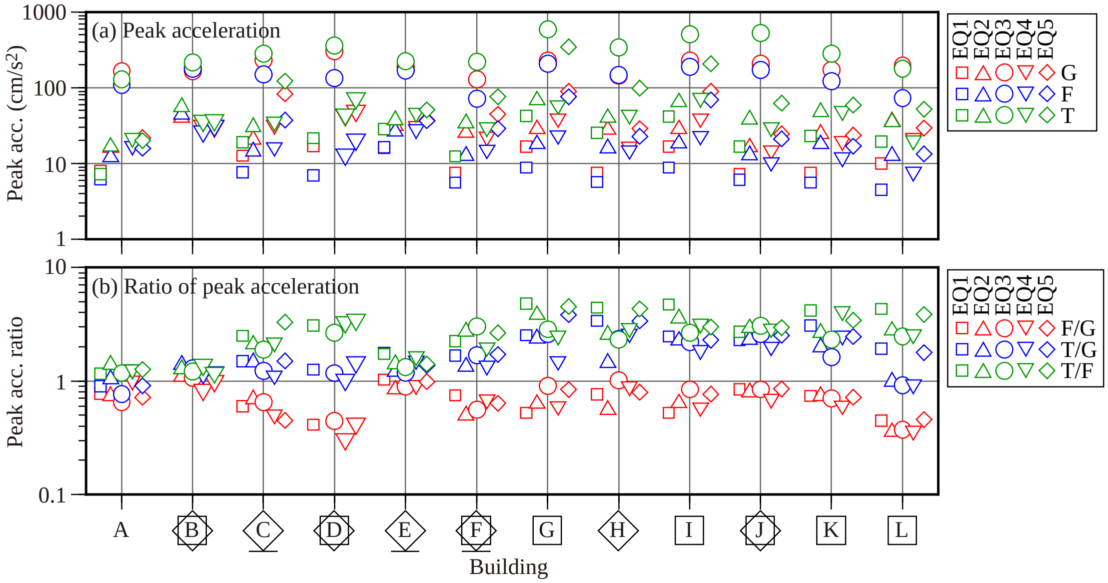

Fig. 4 – Peak accelerations and peak acceleration ratios in X-direction of each building

Fig. 5 (a) and Fig. 5 (b) plot the peak accelerations and peak acceleration ratios in the Y-direction of each building, respectively. The symbols have the same meanings as those in Fig. 4. The general tendency of the peak accelerations is similar to that in the X-direction shown in Fig. 4. Some differences appear in the peak acceleration ratios of the low-rise buildings. The ratios T/G and T/F of the buildings A and B are about 2.0, larger than those in the X-directions. The differences among the buildings are generally small compared with those in the X-direction. This is affected by a difference in vibration mode depending on the direction.

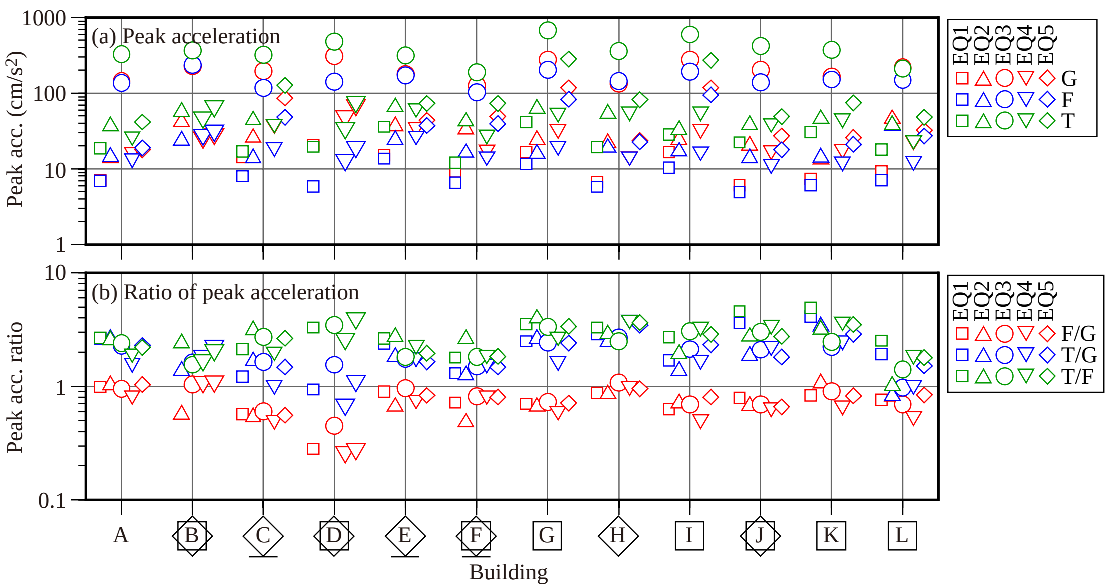

Fig. 5 – Peak accelerations and peak acceleration ratios in Y-direction of each building

5. Change in Dynamic Characteristics

When the physical properties of the ground and/or building change due to severe earthquake motions, the dynamic characteristics of the systems is supposed to be influenced. Therefore, the change in natural periods and damping ratios is discussed in this chapter.

Fig. 6 (a) and Fig. 6 (b) plot identified natural periods (T_{SB}, T_B) and damping ratios (h_{SB}, h_B) based on the strong motion data on five earthquakes in the X-direction of each building, respectively. Square, triangle, circle, inverted triangle and diamond symbols represent EQ1, EQ2, EQ3, EQ4 and EQ5, respectively. Red and blue symbols correspond to the values of the swaying-building system and building system, respectively. Fig. 6 (c) indicates the ratios of the natural periods of EQ2 to EQ5 to those of EQ1. Fig. 6 (d) shows the ratios of the natural periods of the swaying-building system (T_{SB}) to that of the building system (T_B).

Looking at Fig. 6 (a), apparent differences between T_{SB} and T_B are found in buildings A, B and E. As known from Fig. 6 (d), the T_{SB} values of those buildings are two to four times larger than the T_B values. T_{SB} of other buildings are not so different from T_B. Comparing the natural periods identified from different earthquakes, a clear change is observed in the buildings G through K. The natural periods of those buildings increased 20% to 40%, which was caused by the Tohoku Earthquake (EQ3). The natural periods of these building by EQ4 and EQ5 were similar to or longer than that of EQ3. The effect of swaying on those buildings is small because the natural period ratios are nearly 1.0 as shown in Fig. 6 (d). Therefore, any change in natural period was caused due to structural and/or non-structural damage to the buildings by the Tohoku Earthquake.

Looking at the damping ratios in Fig. 6 (b), large values of h_{SB} are found for the buildings A and B. There is a possibility that the identification was failed due to noisy data on the strong motion. Generally, large differences between h_{SB} and h_B are observed in low-rise buildings.

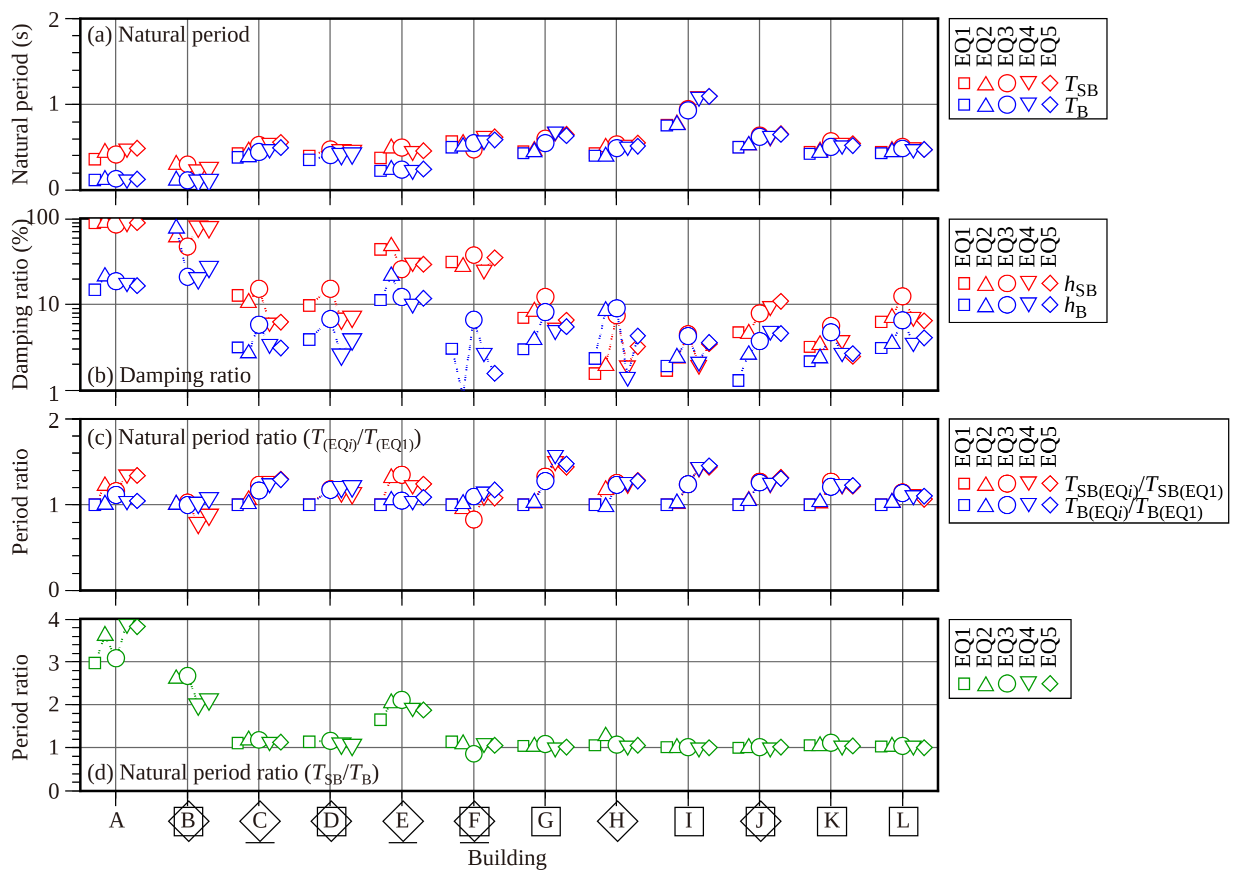

Fig. 6 – Natural periods, damping ratios and natural period ratios in X-direction of each building

Fig. 7 (a) and Fig. 7 (b) plot identified natural periods (T_{SB}, T_B) and damping ratios (h_{SB}, h_B) in the Y-direction of each building, respectively. The meanings of the symbols are the same as those in Fig. 6. Differences between T_{SB} and T_B in the Y-directions of the buildings A, B and F are small in comparison with those in the X-direction. It suggests that the swaying effect may be significantly affected by the plane shape of the building. The trend toward an increase in natural period caused by the Tohoku Earthquake is also observed in the X-direction.

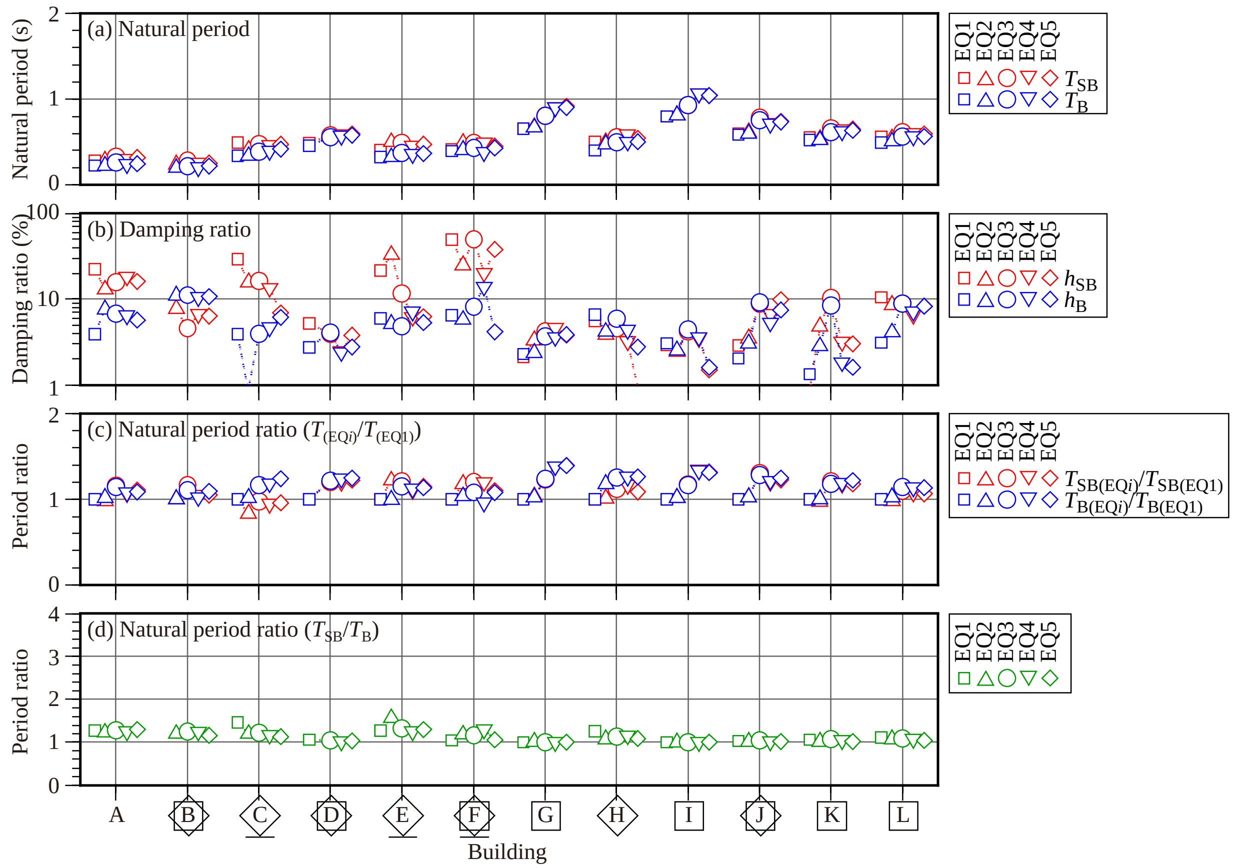

Fig. 7 – Natural periods, damping ratios and natural period ratios in Y-direction of each building

6. Input Loss of Seismic Motions

The difference between the earthquake motions on the ground and at the building foundation is known as the kinematic soil-structure interaction. It is also discussed in terms of the input loss of the seismic motions. The input loss must be a function of the period (or frequency) affected by various parameters, such as the building properties, foundation type, embedment, ground condition, and so on.

Fig. 8 shows Fourier amplitude spectrum ratios between data on the strong motion data on the ground and at the building foundation in the X-direction of each building. In the calculation of the spectrum ratio, the spectra are smoothed using the Parzen window with the window width of 0.1 Hz. The Fourier amplitude ratio represents the input loss of the seismic motion assuming that the input position is the ground surface. Red lines indicate Fourier amplitude spectrum ratios of the strong motion data of the Tohoku Earthquake (EQ3). Blue lines represent the spectrum ratios of EQ1 and EQ2, which are the earthquakes before the Tohoku Earthquake. Green lines correspond to the earthquakes EQ4 and EQ5, which are the aftershocks of the Tohoku Earthquake. Grey dashed and dotted lines indicate the natural periods of the swaying-building system ((T_{SB}) and the building system (T_B) in the X-direction of each building during the Tohoku Earthquake, respectively.

Although the shapes of the spectrum ratios vary among the buildings, the spectrum ratios generally decrease in the short period range and have flat shapes in the long period range. The spectrum ratios of some buildings have a peak around the border of the flat zone. It seems that the peaks of the buildings having basement floors are low. A clear correlation cannot be observed between the shape of the spectrum ratios and the natural periods.

Paying attention to the differences among the earthquakes, the change in the shapes of the spectrum ratios between the before and after the Tohoku Earthquake can be observed in the buildings C, D, G, H and K. The periods, in which the spectrum ratios change from the low to flat zones, increased in those buildings after the Tohoku Earthquake. It is considered that some changes occurred on the ground and/or at the building foundation by the Tohoku Earthquake.

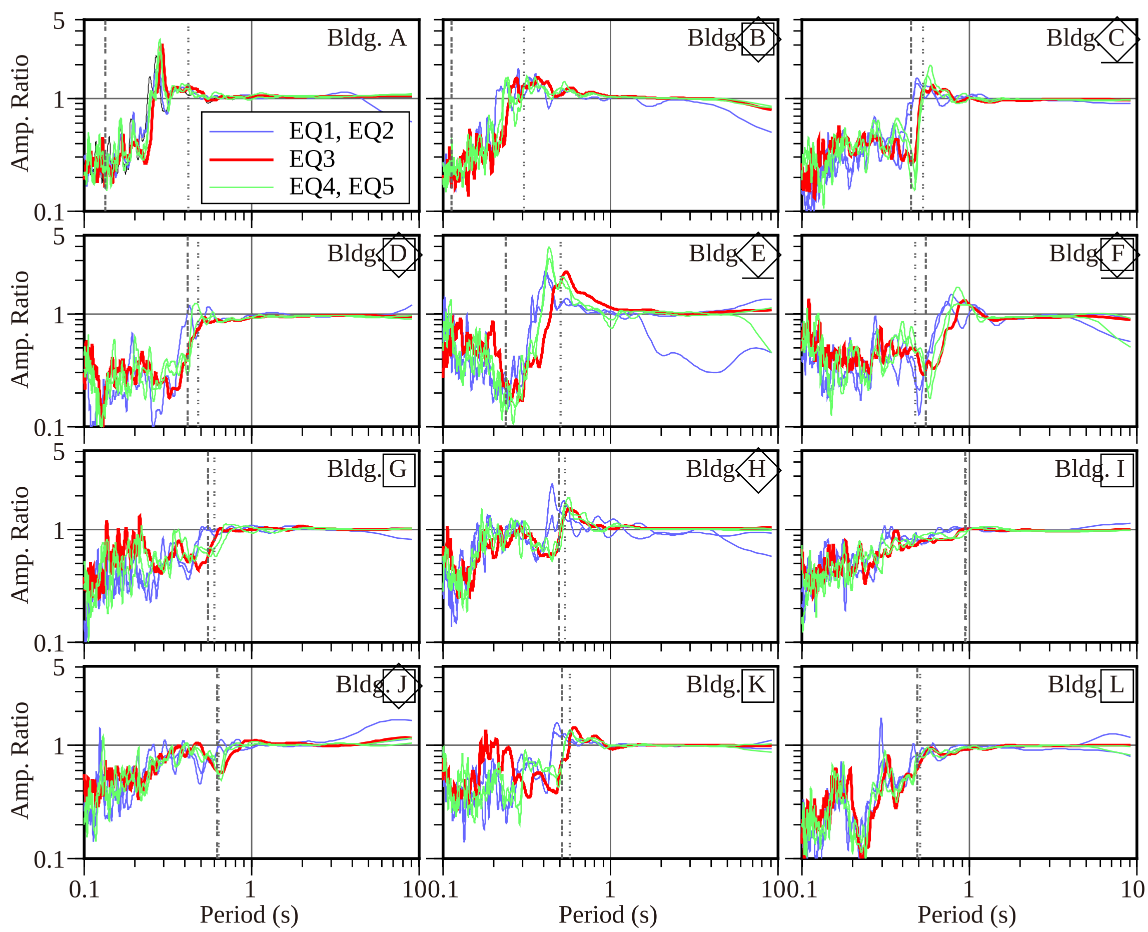

Fig. 8 – Fourier amplitude ratios of building foundation to ground surface in X-direction of each building

Fig. 9 plots the Fourier amplitude spectrum ratios between data on the strong motion data on the ground and at the building foundation in the Y-direction of each building. The meanings of lines are the same as those in Fig. 8. Grey dashed and dotted lines indicate the natural periods TSB and TB in the Y-direction of each building for the Tohoku Earthquake, respectively.

The shapes of the spectrum ratios are similar to those in the X-direction. However, small differences can be found among some buildings. For instance, the spectrum ratios of row-rise buildings, such as the buildings A and B, have different shapes in the short period range between the X- and Y-directions. The spectrum ratios in the Y-directions of the buildings B, E and K have a larger variation in the short period range than in the X-direction.

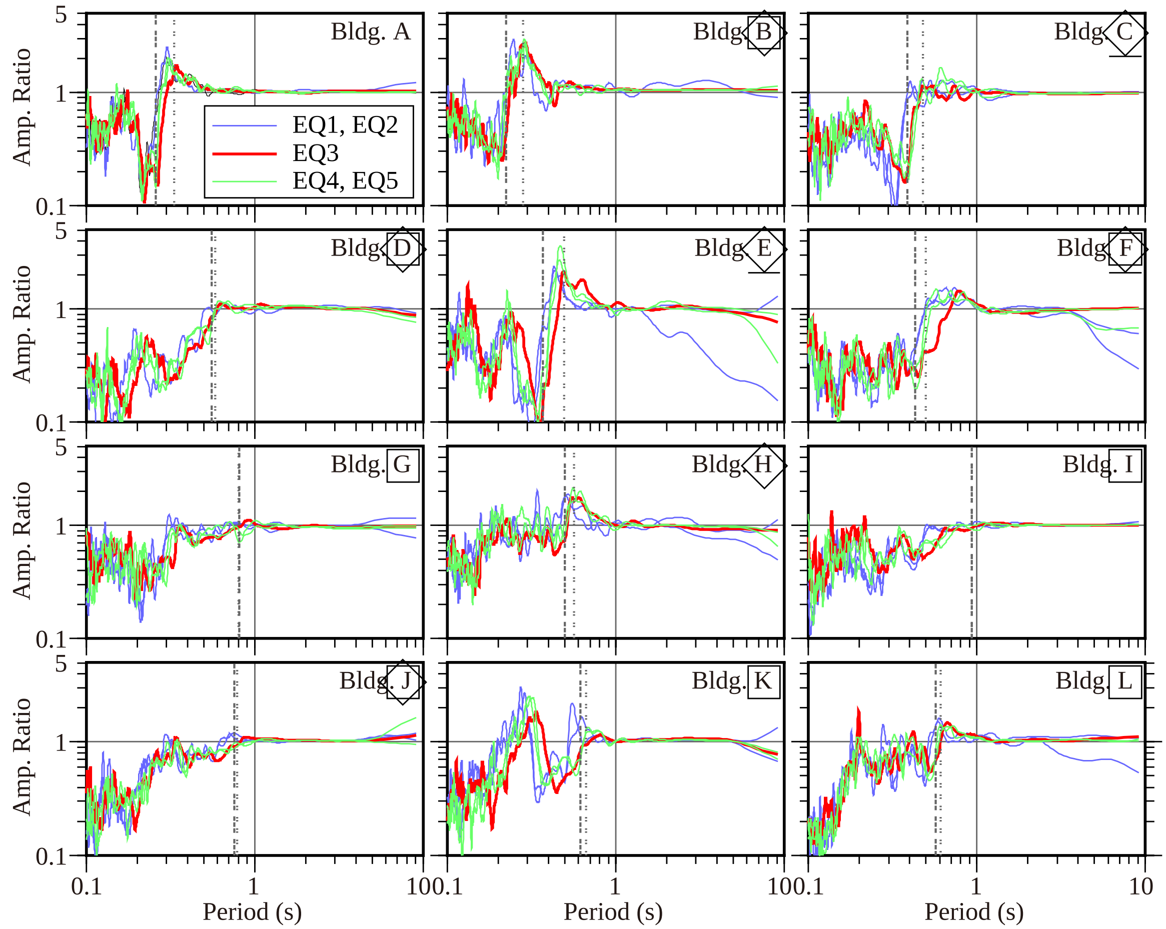

Fig. 9 – Fourier amplitude ratios of building foundation to ground surface in Y-direction of each building

7. Conclusions

Dynamic characteristics of twelve buildings are discussed considering the swaying effect based on strong motion data of five earthquakes including the Tohoku Earthquake.

The ratio of peak acceleration at the building foundation to the ground (F/G) has values between 0.3 and 1.0 and widely varies among the buildings. The ratio of peak acceleration at the building top to the ground (T/G) is distributed between 1.0 and 4.0 and are small in low-rise buildings. The swaying effect is relatively large in the small buildings.

Comparing the natural periods of the swaying-building and building systems, an increase in natural period was observed in all cases. In the long side (X) directions of low-rise buildings, such as the buildings A, B and E, the differences were relatively large. A difference in damping ratio between the swaying-building and building systems was also big in the low-rise buildings. The natural periods of the meddle-rise buildings became longer after the Tohoku Earthquake than before. This may cause seismic damage to the buildings.

The Fourier spectrum ratio of the acceleration data at the building foundation to the ground decreased in the short period range in all the cases. As contrast with the complicated shapes in the short period range, the spectrum ratios in the long period range were about 1.0 and flat. In some buildings, a difference in spectrum ratio was observed between before and after the Tohoku Earthquake.

The soil-structure interaction may be affected by various parameters, such as the building properties, foundation type, embedment, and ground condition. We need a further investigation in order to discuss the contribution of those parameters to the seismic response of buildings.

8. Acknowledgements

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