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SPATIAL VARIATION OF RESPONSE OF HIGH-RISE BUILDINGS SUBJECTED TO LONG PERIOD GROUND MOTION OF THE NANKAI TROUGH EARTHQUAKE

Y. Suzuki(1), K. Kanda(2), M. Abe(3), H. Fujiwara(4), N. Morikawa(5), T. Maeda(6)

(1) *General Manager, Kobori Research Complex Inc., y-suzuki@kobori-takken.co.jp*
(2) *Principal Researcher, Kobori Research Complex Inc., kandak@kobori-takken.co.jp*
(3) *Manager, Kobori Research Complex Inc., masashi-abe@kobori-takken.co.jp*
(4) *Director, National Research Institute for Earth Science and Disaster Resilience, fujiwara@bosai.go.jp*
(5) *Chief Researcher, National Research Institute for Earth Science and Disaster Resilience, morikawa@bosai.go.jp*
(6) *Chief Researcher, National Research Institute for Earth Science and Disaster Resilience, tmaeda@bosai.go.jp*

Abstract

In the 2003 Tokachi-oki earthquake, an oil tank fire broke out in Tomakomai, far from the epicenter, and long-period ground motions characterized by long-period vibrations continued for a long time. The 2011 off the Pacific coast of Tohoku Earthquake, which caused unprecedented damage, reminded us of the importance of dealing with earthquakes beyond expectations. During the earthquake, long-period ground motions were observed in Tokyo and Osaka, which is farther away, and it was reported that high-rise buildings were shaken greatly. On the other hand, it has been a long time since the danger of a huge earthquake along the Nankai Trough was pointed out. Earthquakes along the Nankai Trough have been known to have occurred repeatedly in the history. It has been pointed out that it may have a greater impact on metropolitan areas than the 2011 off the Pacific coast of Tohoku Earthquake.

Therefore, in the large metropolitan areas in Tokyo, Aichi, and Osaka, where there are many high-rise buildings, the response of high-rise buildings to the Nankai Trough earthquake is evaluated, the degree of damage is grasped, and regional characteristics are examined. As input ground motion, for multiple Nankai trough long-period seismic motions evaluated by the differential method assuming multiple seismic motion occurrence patterns, the seismic ground motion that has the average response spectrum considering the weight set for each occurrence pattern is selected. In addition, seismic motion with an average + σ considering variation is selected. These ground motions are evaluated in each metropolitan area. Using these as input seismic motion, time history response analysis is performed using multiple high-rise building models set considering the structural type (steel structure / RC structure), building height, span length, etc. Thereby, building response is evaluated for each region. Using the results, regional characteristics of the building response are summarized and the correlation with the response spectrum value of the ground motion is considered.

Keywords: response analysis; high-rise building; long-period ground motion; Nankai Trough earthquake

1. Introduction

In recent years, there has been concern about a huge earthquake that originates along the Nankai Trough. When the earthquake occurs, in the three major metropolitan areas, Tokyo, Aichi and Osaka, which are highly metropolitan areas where administrative and economic functions are highly concentrated, it is assumed that long-period ground motions in which large slow vibrations continue for a long time [1]. Long-period ground motions have little effect on medium- and low-rise buildings which have relatively short fundamental periods, but have a large effect on relatively long-period buildings, including high-rise buildings and there is concern that damage will occur [2].

Long-period ground motions were re-recognized in the 2003 Tokachi-oki Earthquake after a fire broke out and damaged oil storage facilities in Tomakomai, more than 100 km away from the epicenter [3]. Furthermore, in the 2011 off the Pacific coast of Tohoku Earthquake, long-period ground motion caused large-scale vibrations of high-rise buildings in Tokyo and Osaka far away from the epicenter, causing damage due to shaking [4, 5, 6]. When an earthquake occurs with the epicenter along the Nankai Trough, where future outbreaks are a concern, in a metropolitan area where high-rise buildings are concentrated, it is expected that the amplitude will greatly exceed the shaking caused by long-period ground motions experienced in the past [7]. Therefore, it is very important to predict in advance the magnitude of long-period ground motions expected in a metropolitan area when a large earthquake occurs, and to predict in advance the magnitude of the vibration of a skyscraper building there. At the same time, it is necessary to take measures against the shaking.

In this study, the long-period ground motions evaluated in the Nankai Trough earthquake were used. The target areas were metropolitan areas near Tokyo, Aichi and Osaka, where there are many high-rise buildings. Then, the response of high-rise buildings to the evaluated ground motions was estimated. Long-period ground motions have been prepared for many cases using the methods in the past papers [8, 9]. Among them, a study case that gives an average level at a specific point was selected and used as long-period ground motions for study in that area. In addition, six types of high-rise building models were created in consideration of the diversity of skyscrapers in consideration of differences in structural type, building height, and span length. Then, the time history response analysis was performed using the set long-period ground motion for study and the high-rise building model. The maximum responses were displayed on a map. And the regional characteristics were summarized. In addition, the correlation between the building response and the spectral values of the input ground motions and long-period ground motion indices proposed [10] was discussed. And a simple response estimation method for high-rise buildings was tried using the results.

2. Selection of input ground motions

Concerning about the Nankai Trough earthquake, long-period ground motions have been created in consideration of variation, by the three-dimensional difference method, assuming various epicenters and occurrence patterns [8, 9]. The fundamental natural period of the building, which will be described later, of 3 seconds or more is within the range of the effective period determined by mesh division size.

There is a total of 469 long-period ground motion calculation cases. As for the seismic pattern, a total of 15 cases shown in Fig. 1 were calculated for multiple cases with common occurrence patterns and different parameters. Weights set by expert judgement were set for each assumed occurrence pattern in consideration of the occurrence frequency (Table 1). The average and the average plus standard deviation response spectra were calculated in consideration of the weighting factors set with the frequency of occurrence in mind at three locations: Aichi Prefectural Office, Osaka Prefectural Office, and Tokyo Metropolitan Office. The case with the response spectrum closest to the average or average + σ spectrum was extracted as a study case used in each of the three regions. In this study, the case where the error of the pseudo-speed response spectrum from 3 seconds to 8 seconds is minimized is selected. Then, the ground motion for each 2 km mesh was extracted for this case and adopted as the input ground motion for examination.

Fig. 2 shows the pseudo-velocity response spectrum of Tokyo as a representative of the three regions. These spectra were evaluated at Tokyo metropolitan office location. The average spectrum and average plus standard deviation spectrum for many study cases, and the ground motion spectra selected as having spectra close to the average and average + σ spectra were shown superimposed.

Fig. 3, Fig. 4 and Fig. 5 show the spatial distribution of the 5% damped pseudo-velocity response spectrum of the study case selected as described above. The portions painted black are those where the ${}_pS_v$ exceeds 500 cm/s. In the maps, the railway lines (JR) are indicated by red lines, and the rivers are indicated by light blue lines. And red triangle symbols show locations of local government offices.

The characteristics of the spatial distribution of the ground motion are listed below.

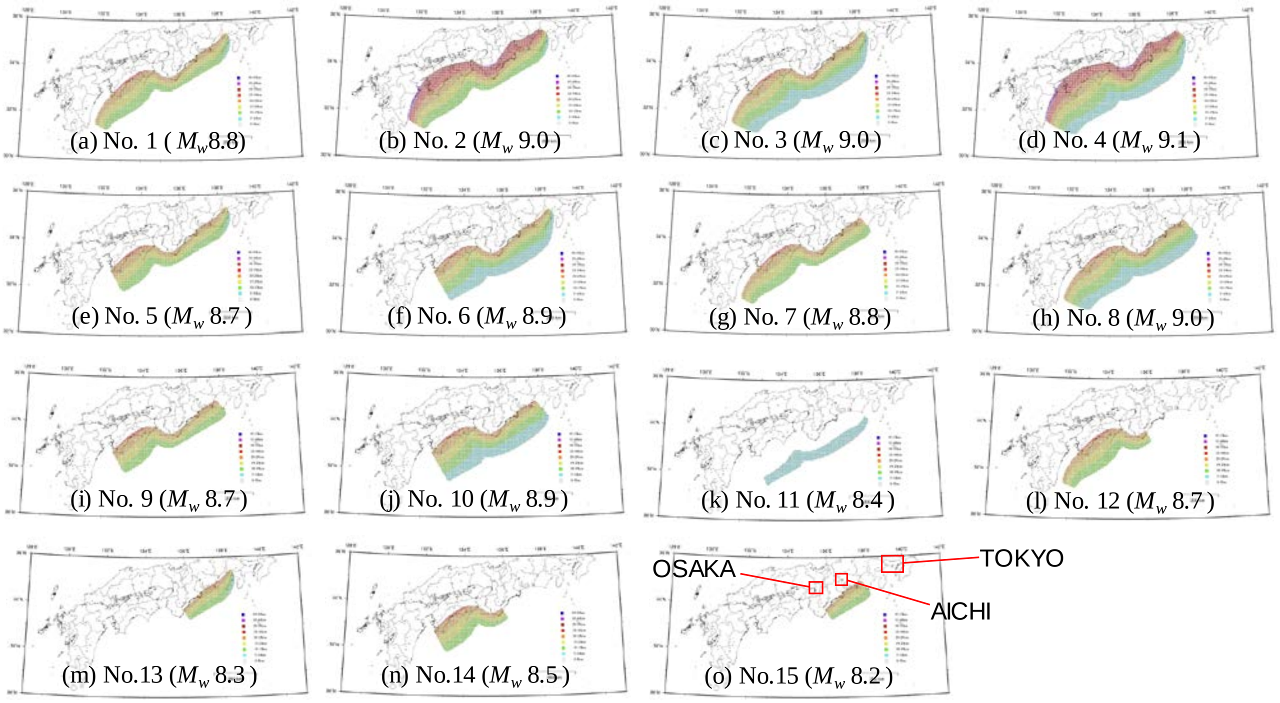


Fig. 1 – Assumed hypocenter maps

Table 1 –Weighting factor

Assumed Hypocenter No.		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	sum.
cal. Number		12	6	12	107	36	170	6	12	12	12	9	9	22	22	22	469
weight	AICHI	0.0125	0.0125	0.0125	0.0125	0.1625	0.1625	0.0125	0.0125	0.0250	0.0250	0.0500	0.0000	0.3750	0.0000	0.1250	1.0000
	OSAKA	0.0125	0.0125	0.0125	0.0125	0.1625	0.1625	0.0125	0.0125	0.0250	0.0250	0.0500	0.0750	0.0000	0.4250	0.0000	1.0000
	TOKYO	0.0125	0.0125	0.0125	0.0125	0.1625	0.1625	0.0125	0.0125	0.0250	0.0250	0.0500	0.0000	0.3750	0.0000	0.1250	1.0000

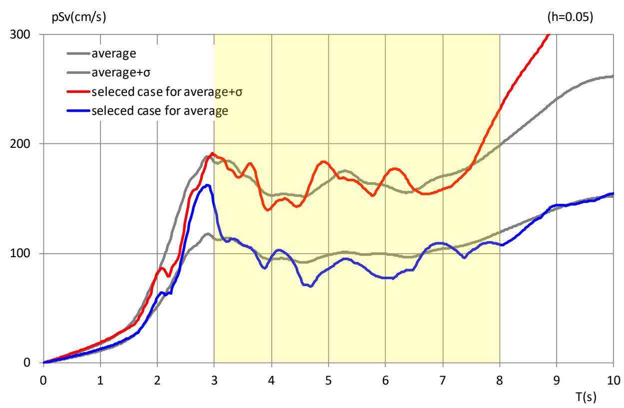


Fig. 2 – Velocity response spectra at Tokyo local government location (average and average + σ)

<AICHI>

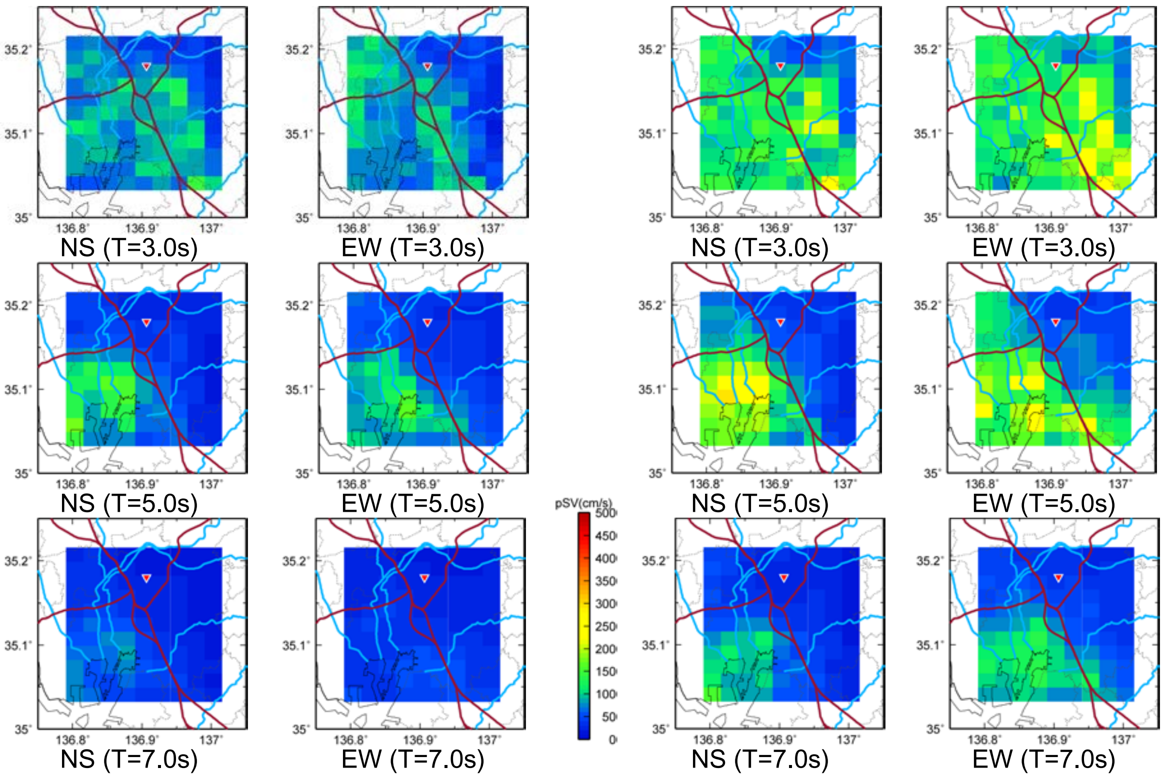
From the upper right (land side) to the lower left (sea side) of the map, the period of the increase in psudo-velocity spectrum amplitude varies from 3 seconds to 5 seconds. At the average level, it is generally less than 200 cm/s in all areas, but at the average + σ level, there are areas where the amplitude is about 200 cm/s.

<OSAKA>

The characteristics of OSAKA are that there is a striped area extending in the north and south of the inland where the period from 5 to 6 seconds is dominant, and a bay area where the period from 6 to 8 seconds is dominant. In average ground motions, there is a limited area where the spectral amplitude is about 200 cm/s. At average + σ ground motions, the spectral amplitude exceeds 400 cm/s in the bay area and part of the inland.

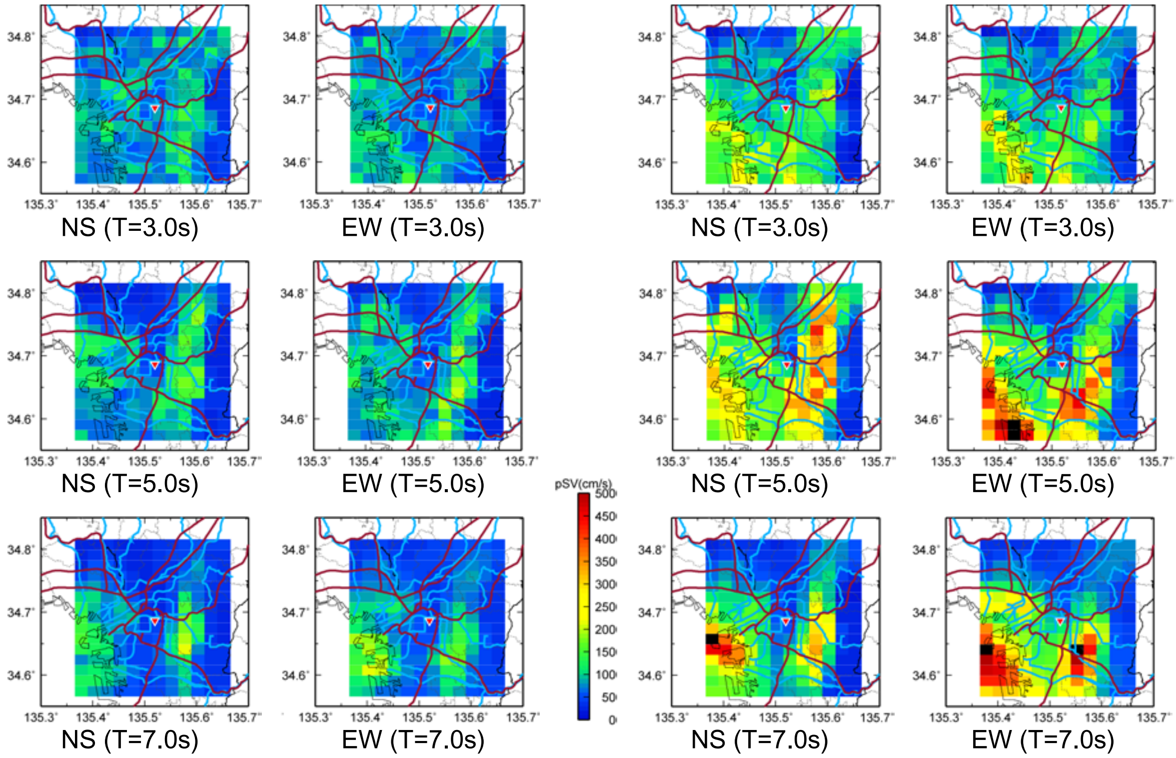
<TOKYO>

In a map of 3 seconds, there is a region where the spectral amplitude becomes streaky in the east and west of the map. In the lower right part of the map (the bay area), the spectrum amplitude is larger in a longer period than on the land side. At the average level, there is a local portion having a spectral amplitude of at most about 200 cm/s. At the average + σ level, there are areas where the amplitude is about 300 cm/s in a 7 second period.



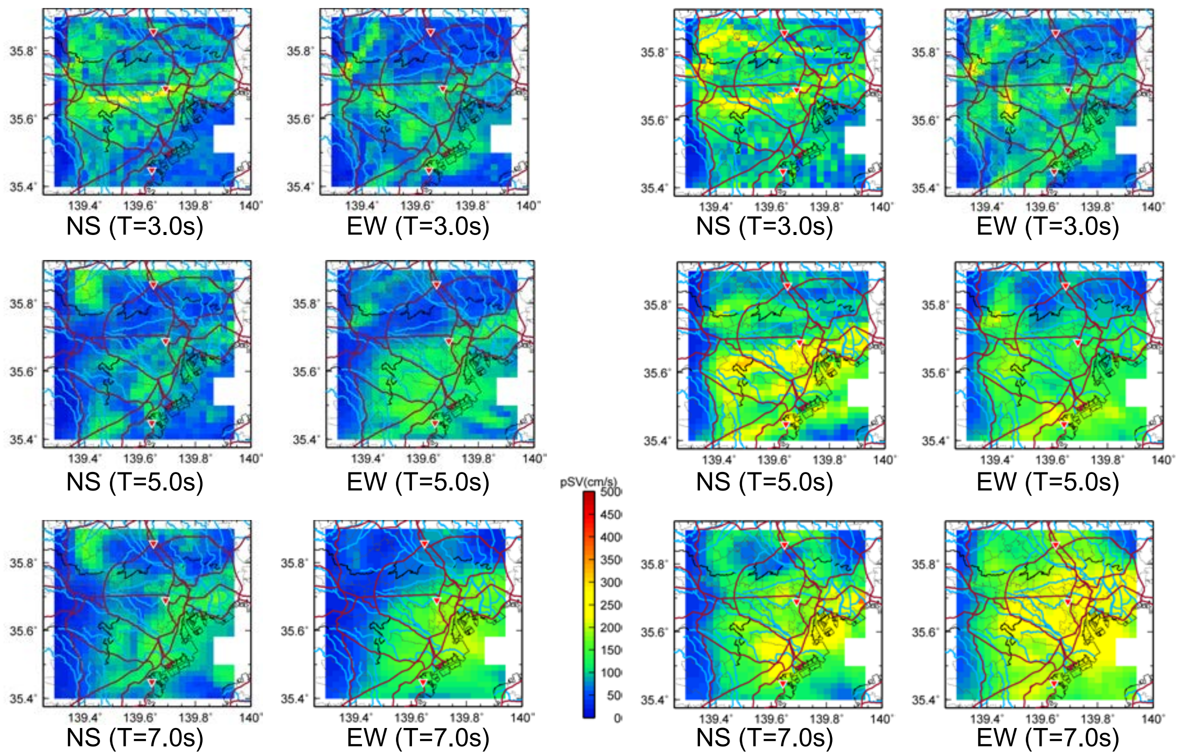
(a) AICHI average (b) AICHI average+σ

Fig. 3 – Pseudo velocity maps at *T*=3, 5 and 7 sec. in AICHI region



(a) OSAKA average (b) OSAKA average+σ

Fig. 4 – Pseudo velocity maps at T=3, 5 and 7 sec. in OSAKA region



(a) TOKYO average (b) TOKYO average+σ

Fig. 5 – Pseudo velocity maps at T=3, 5 and 7 sec. in TOKYO region

3. High-rise building response analysis model

In the time history response analysis of a high-rise building, various analysis models are used, from an equivalent shear type model that aggregates the characteristics of each story into one, to a three-dimensional frame analysis model that models each of the building components. In this study, a two-dimensional frame analysis model was adopted in consideration of the accuracy of the response evaluation and the computational load, because many time history response analyzes were performed. Since it is assumed that the moment frame has a rectangular planar shape and the characteristics of each frame do not differ greatly, appropriate response evaluation can be performed.

The number of floors is assumed at 30, 45 and 60 in consideration of the existing skyscrapers and the prevailing period of long-period ground motions in the metropolitan area. In addition to the steel frame building of the moment frame structure having equal spans of three different heights (S30, S45, S60), two types with different span lengths (S45X, S45Y) will be adopted. Furthermore, a 40-story reinforced concrete building (RC40) was added. Fig. 6 shows six model buildings.

The response analysis to the input ground motion required by the current standard was performed for six types of high-rise building models. It has been confirmed that the building models are properly designed in comparison with the seismic safety criterion, which is generally set to a maximum story deformation angle of 1/100 or less and a plasticity factor of 4 or less. A list of the fundamental natural periods of the created high-rise building model is shown in Table 2.

Time history analysis was conducted with six models against selected long period ground motions. In the analysis, the yielding of beams was considered.

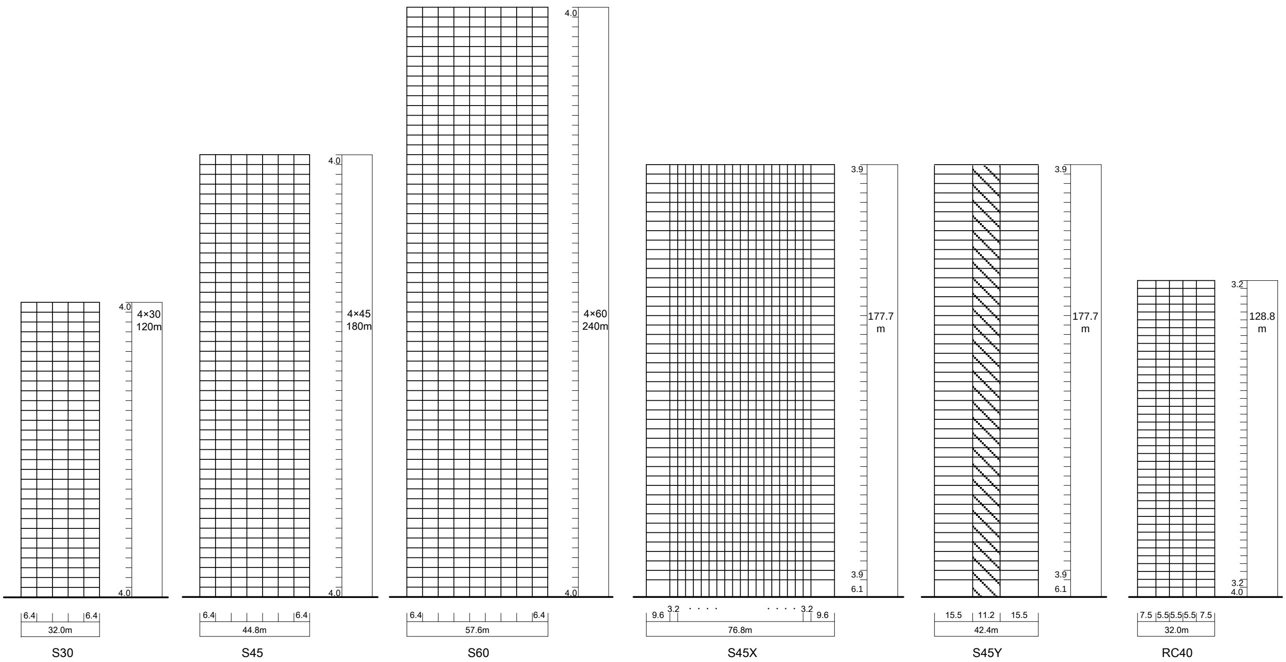


Fig. 6 – Time history response analysis models of super high-rise buildings

Table 2 – Fundamental natural Period (sec.)

	S30	S45	S60	S45X	S45Y	RC40
Fundamental Period (sec.)	3.70	5.36	6.49	3.82	4.99	2.55

4. Response evaluation of high-rise buildings

Fig. 7 shows the maximum story drift ratio of each model building. Black fill indicates that the story drift ratio is over 2%. In Tokyo, there are scattered areas where the story drift ratio is large not only in the bay area but also in the inland. This may be due to the complex deep subsurface structure and the direction of seismic wave incidence. In Aichi, the response is greater on the Ise Bay shore southwest of the vicinity of the JR Tokaido Line. In Osaka, the response is large in the bay area and the alluvial plain in the Kawachi plain, and small in the plateau. In Aichi and Osaka, it is presumed that long-period ground motions in the bay area and alluvial plain is dominated by the deep ground structure. Therefore, it is considered that there is little difference in the magnitude of the ground motion and the responses in the NS direction and the EW direction.

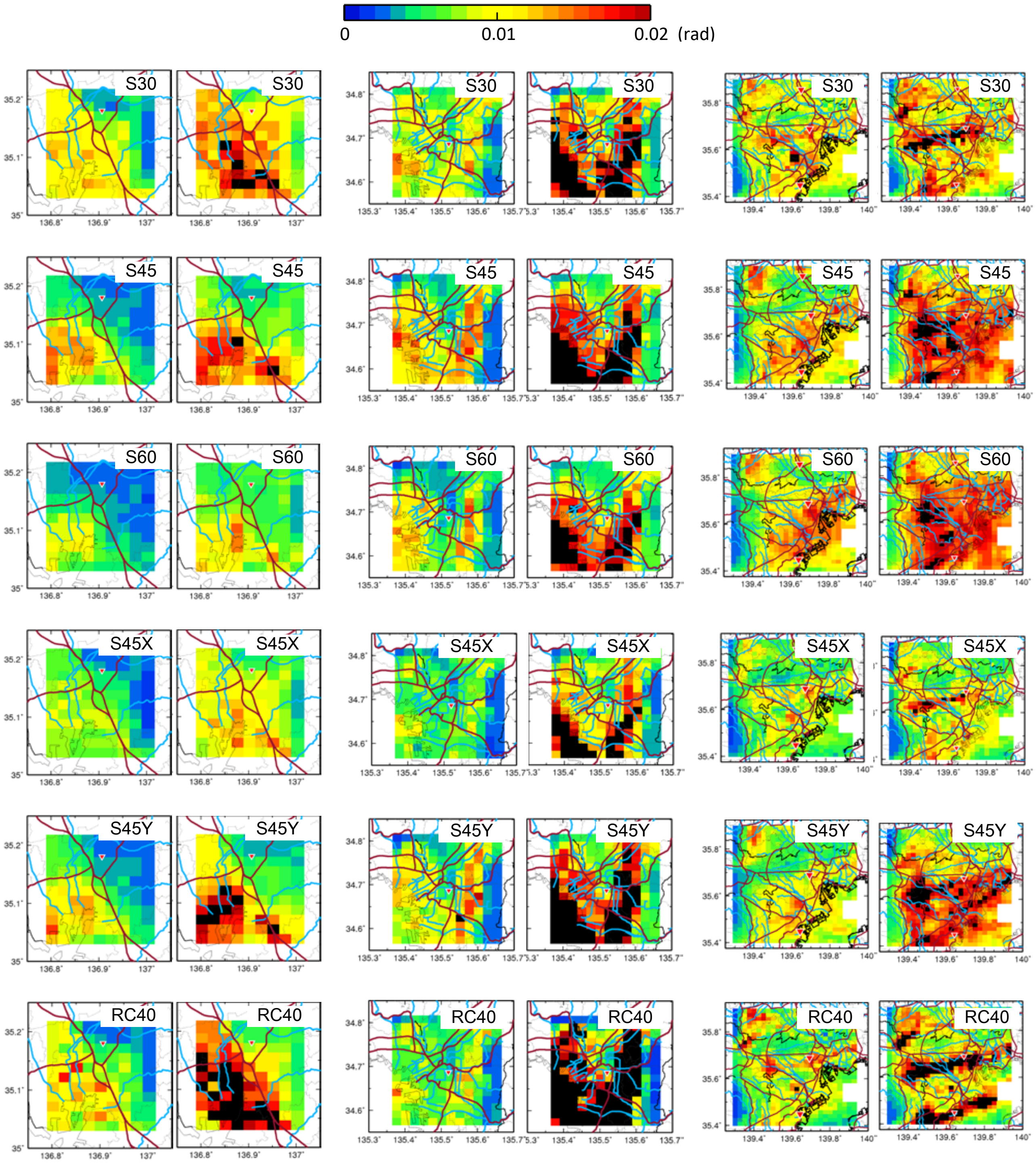
Since the periodic component of the ground motion corresponding to the primary vibration mode of the building has been appropriately evaluated by the Finite Deference method, it is considered that the response of the tall building shown here has been generally evaluated appropriately. However, in the effective period range, the response of the higher-order vibration mode of the building has not been properly evaluated. The Iwaki method [16] has been proposed as a method for relatively good evaluation of the short-period component of seismic motion corresponding to higher-order vibration modes, and its application to the Nankai Trough earthquake is expected.

In this study, a high-rise building is modeled taking into account only the yielding of beam members because the yielding of beams takes place prior to column yielding. In the case of a large building response with a story drift ratio exceeding 2%, the possibility of not only beams but also columns being significantly damaged increases [17]. Therefore, damage assessment of column members remains as another issue.

5. Considerations on regional differences

The relationship between the maximum response value of a high-rise building to long-period ground motion and the 5% velocity response spectrum in the plains of Aichi, Osaka and Tokyo was compared between regions. Here, the maximum story drift ratio is taken as a representative of the index indicating the magnitude of the building response. So the relationship with the maximum velocity response value $S_v(T_1)$ of the single pendulum of the first natural period having a damping of 5% is organized. For steel buildings, the spectral values at the first natural period are used (Fig. 8). For reinforced concrete buildings, the stiffness decreases due to cracking and the equivalent stiffness decrease after member's yielding are assumed from relatively small amplitude. Therefore, in the RC building, cases where the 1st natural period, when members was assumed to be elastic, was increased 1.5 times or 2 times assuming a decrease in stiffness were arranged (Fig. 9). And the correlation coefficient between the maximum story deformation angle γ and the maximum velocity response value $S_v(T_1)$ of a single pendulum having a T_1 period was calculated for the responses in three regions (Table 3).

According to Fig. 8. and Fig. 9, there is almost no difference in the correlation between the maximum response and the maximum velocity response value $S_v(T_1)$ of the single pendulum in the first-order natural period in the suburbs of Tokyo, Aichi, and Osaka. Regarding steel buildings, the differences due to the building height and span length are small, and the maximum responses of buildings have a high correlation with the maximum velocity response value $S_v(T_1)$ of the single pendulum. The correlation coefficient evaluated for the three regions is very high, about 0.85 to 0.95. However, as the input level increases, the variation tends to increase, which is considered to be caused by a change in response characteristics due to plasticization. In a reinforced concrete building, the relationship with the maximum velocity response value $S_v(T_1)$ of a single pendulum varies greatly from the range where the spectrum value is small. And most correlated with S_v (T_1 x 1.5) which is the response at the period 1.5 times the elastic fundamental period. Further, in the range of a large input where S_v exceeds 200 cm / s, the correlation is further increased with respect to a spectral value twice the first period. In fact, the correlation coefficient of the RC building is the largest for a single pendulum response with a period of 1.5 times the primary natural period, and the correlation coefficient exceeds 0.85. This shows that it is necessary to consider a certain degree of stiffness reduction concerning about RC buildings.



(1)average (2) average+σ (1)average (2) average+σ (1)average (2) average+σ

(a) AICHI (b) OSAKA (c) TOKYO

Fig. 7 – Response story drift ratio maps

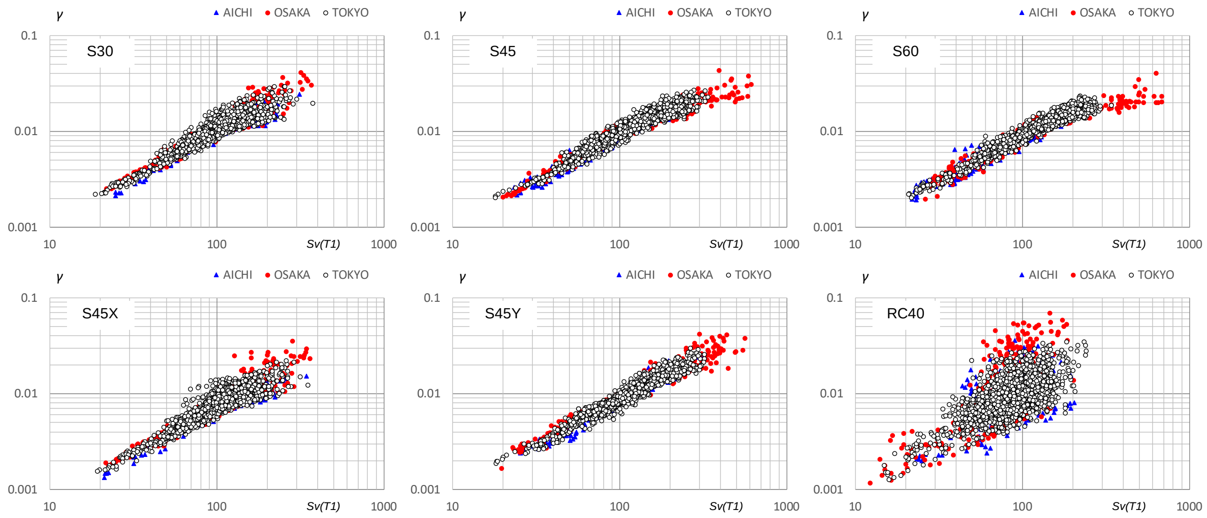


Fig. 8 – Relation between story drift ratio γ and response velocity $S_v(T_1)$ (cm/s, 5%)
(S30, S45, S60, S45X, S45Y, RC40)

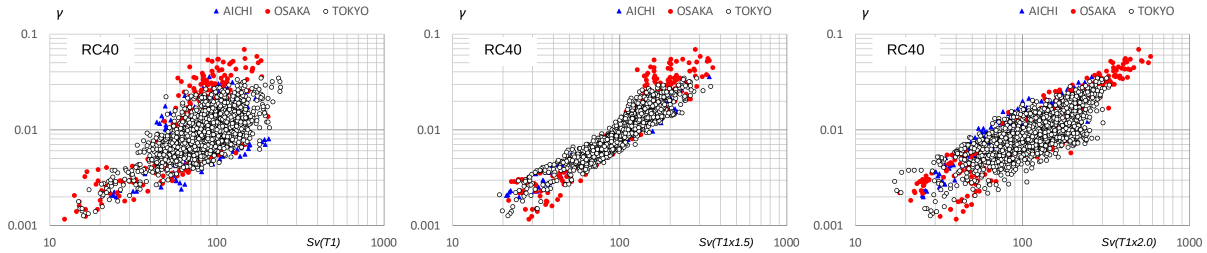


Fig. 9 – Relation between story drift ratio γ and
response velocity $S_v(T_1)$, $S_v(T_1\text{x}1.5)$ and $S_v(T_1\text{x}2.0)$ (cm/s, 5%) (RC40)

Table 3 – Correlation coefficient between story drift ratio γ and response velocity $Sv(T_1)$ (cm/s, 5%)

	Correlation Coefficient		Correlation Coefficient
S30	0.8808	RC40 at T_1	0.4800
S45	0.9129	RC40 at T_1 x1.5	0.8582
S60	0.8974	RC40 at T_1 x2.0	0.8247
S45X	0.8504		
S45Y	0.9420		

6. Trial of simple response estimation of high-rise building

It was confirmed that the maximum velocity response value $S_v(T_1)$ of the single pendulum in the first natural period of each building and the maximum story deformation angle had a high correlation. In other words, it is possible to estimate the response of a high-rise building without calculating the response to long-period ground motions. However, it is difficult to use the maximum velocity response value $S_v(T_1)$ of the single pendulum for the natural period of each building for predicting the response of many buildings. Here, assuming that some estimation error is allowed, a response spectrum average ${}_aS_v$ over a wide period range is adopted as an index for maximum response estimation. The period range is 1.6 seconds to 7.8 seconds, referring to the JMA long-period seismic intensity class [10]. In addition, the relationship between the long-period ground motion indices

I_{L1}, I_{L2}, and I_{L3} proposed in Reference [10] and the maximum response story drift ratio is also confirmed (Fig. 10, Table 4). I_L is proposed as a seismic intensity corresponding to long-period ground motions. I_{L1}, I_{L2} and I_{L3} are three kinds having different filter characteristics in the frequency domain. The target period differs for each index, and the target period of the index is long in the order of I_{L1}, I_{L2}, and I_{L3}.

In any of the indices, although the correlation coefficient is smaller than the maximum velocity response value $S_v(T_1)$ of the single pendulum in the first natural period, it can be an appropriate index for estimating the building response. For the response spectrum average ${}_aS_v$ having the largest correlation coefficient among the four indices, an approximate curve (eq. 1) is set, and the coefficient of determination at that time is shown in the figure. For example, it can be said that the magnitudes of the input ground motions that reach the maximum story drift ratios of 1% and 2% are 94 cm / s and 196 cm / s with an average ${}_aS_v$ of 5% velocity response spectrum. Fig. 11 shows the spatial distribution of ${}_aS_v$. The distribution is obtained by averaging the response spectrum values for each period from 1.6 seconds to 7.8 seconds. Fig. 12 shows the result of estimating the maximum story drift ratio of a high-rise building using the approximate curve. This figure shows the average response of a number of skyscrapers. Comparing Fig. 12 with Fig. 7, in the various building models in Fig. 7, the area where the building response is large matches the area where the large response is also predicted in Fig. 12.

$$\gamma = {}_aS_v^{\,0.939} \times 1.41 \times 10^{-4} \qquad \text{(Coefficient of determination } R^2 = 0.740) \qquad (1)$$

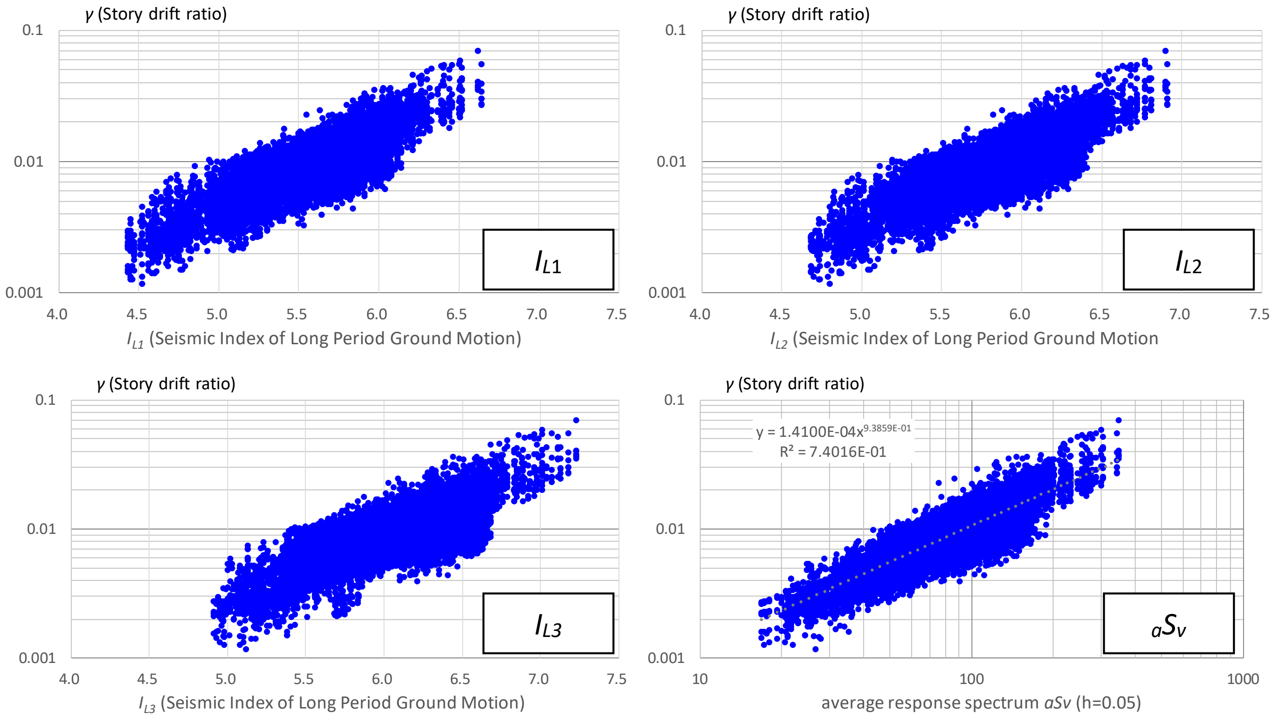
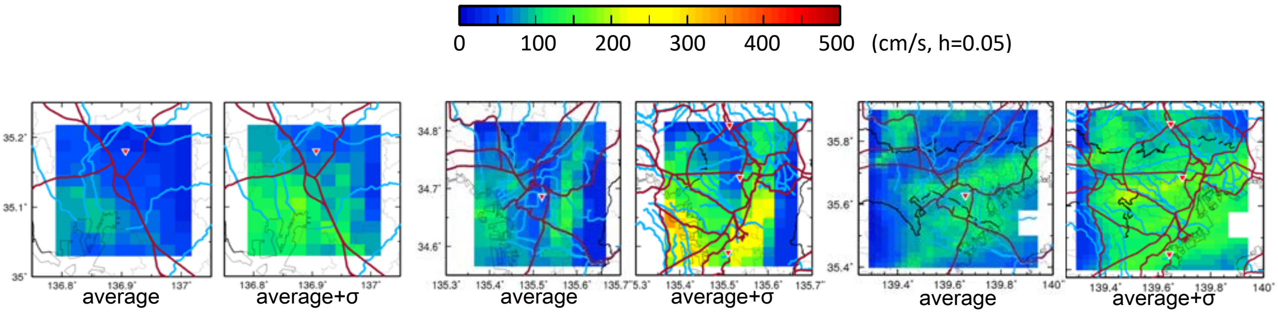


Fig. 10 – Relation between story drift ratio γ and seismic Indices of long period ground motions

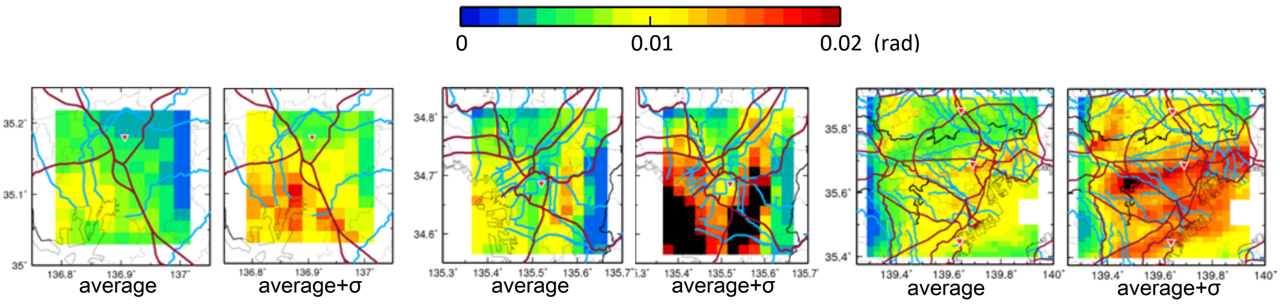
Table 4 – Correlation coefficient between seismic index and story drift ratio

	I_{L1}	I_{L2}	I_{L3}	${}_aS_v$
Correlation Coefficient	0.7575	0.7584	0.7434	0.8265



(a) AICHI (b) OSAKA (c) TOKYO

Fig. 11 – Velocity response spectrum average ${}_aS_v$(cm/s, 5%) maps



(a) AICHI (b) OSAKA (c) TOKYO

Fig. 12 – Story drift ratio estimated from velocity response spectrum average ${}_aS_v$

7. Conclusions

The spatial response distribution of high-rise buildings in the plains near Aichi, Osaka and Tokyo to the assumed earthquake along the Nankai Trough was evaluated.

In Aichi, the response is greater on the Ise Bay shore. In Osaka, the response is large in the bay area and the alluvial plain, and small in the plateau. In Aichi and Osaka, it is presumed that long-period ground motions in the bay area and alluvial plain is dominated by the deep ground structure. In Tokyo, there are scattered areas where the response is large not only in the bay area but also in the inland. This may be due to the complex deep subsurface structure and the direction of seismic wave incidence.

The relationship between the relative velocity response spectrum value at the first natural period of the building and the maximum story drift ratio has a high correlation, especially for steel structures, irrespective of the three regions. And it was found that it is necessary to consider the elongation of the natural period for RC structures because of the decrease in stiffness by component's crack and yielding.

In addition, a method of estimating the maximum story drift ratio γ by the response spectrum average ${}_aS_v$ without performing the time history response analysis of high-rise buildings was tried.

8. Acknowledgements

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