# VARIATION OF LONG-PERIOD GROUND MOTION CAUSED BY SMGA DISTRIBUTION OF THE SAGAMI TROUGH EARTHQUAKE

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## *Abstract*

There are many high-rise buildings in the Kanto region of Japan, represented by Tokyo, and a large earthquake in this area can cause serious damage. In particular, inter-plate earthquakes along the Sagami Trough are destructive earthquakes that have repeatedly occurred in the past (in 1703 and 1923), and there is a concern that they will occur in the near future.

Several studies based on observations of long-period ground motions at sites on the sedimentary plain have reported that the periodic characteristics, amplitudes, and durations of the waves vary with the location of the hypocenter. For an inter-plate earthquake such as the huge earthquake along the Sagami Trough, the source area is assumed to be vast, and therefore, the effect on the strength of the ground motion may differ even within the same source area. Thus, predicting the location of the source area that can considerably contribute to the strength of the ground motion will help employ the strong motion generation area (SMGA) for ground motion prediction.

In this study, we focused on long-period ground motions of the city where high-rise buildings are concentrated, such as Shinjuku (Tokyo Pref.), Marunouchi (Tokyo Pref.) and Chiba (Chiba Pref.), and we investigated areas where ground motions became strong within the source area of the huge earthquake along the Sagami Trough. Using the reciprocity theorem in numerical simulations conducted using the three-dimensional difference method, we calculated Green's Function for the Shinjuku site from each subfault in the assumed source area. We then analyzed the spatial distribution of the velocity response and input energy.

The results of this study indicated that the area close to the site (area 1) and the area where the subfault depth was shallow areas 2 to 5. On comparing the sites, we found that the area where the amplitude is dominant varies depended on the site. Shinjuku and Marunouchi sites, which are relatively close (less than 10 km), have almost the same spatial distribution, but there is a difference in the relationship between area 2 and 4. At Chiba which is far from these two sites, the amplitude is dominant in the area 5 where no dominance was observed at other sites. Furthermore, on comparing the position of SMGA widely used in the practice of structural design for long-period architectures, a large corresponding areas 1 to 5 was observed; however, no SMGA could cover areas 1 to 5 in one cases.

*Keywords: Long-period ground motion, Megathrust earthquake along the Sagami Trough, Kanto basin, Green's function, Reciprocity method*

## 1. Introduction

There are many high-rise buildings in the Kanto region of Japan, represented by Tokyo. A large earthquake here can have an enormous impact on the society. The occurrence of a plate boundary earthquake along the Sagami Trough in the Kanto region is a serious concern. Such earthquakes have repeatedly occurred in the past, at the inter-plate between the Philippine Sea plate and the continental plate beneath the Kanto region. In recent years, the Genroku Kanto Earthquake (1703) and the Taisho Kanto Earthquake (1923) have been cited as destructive earthquakes [1].

Recent government ground motion predictions for inter-plate earthquake along the Sagami Trough include those of the Tokyo Metropolitan Government (TMG) [2], Central Disaster Management Council (CDMC) [3], and Headquarters for Earthquake Research Promotion (HERP) [4]. The former two predictions set fault parameters estimated from past earthquakes; however, the latest prediction considers various fault parameters such as location of strong motion generation area (SMGA) and areas of it [2-4]. However, as the hypocenter area is very large, it is difficult to arrange the SMGA to cover it because of the high computational cost. Fig. 1 shows the hypocenter area and SMGA layout used in the previous earthquake prediction; it is evident that the SMGA cannot cover the entire area.

In relation to the arrangement of the SMGA, several studies with observations of long-period ground motions at sites on the sedimentary plain have reported that their periodic characteristics, amplitude, and duration of wave vary with the location of the hypocenter [5-8]. Zama [5] highlighted that the amplitude and predominant period of ground motions in Tokyo depend on the location of the epicenter, and Ishii [7] indicated that the duration depends on the location of the epicenter. Furumura and Hayakawa [6] examined the propagations of multiple surface waves in the Kanto Plain as a cause for the 2004 Niigata Chuetsu Earthquake, and they suggested that the surface waves merge and the ground motion becomes large. Further, Hirai and Fukuwa [8] performed numerical analysis on an irregular basin structure model and confirmed that Green's Function (the characteristics of propagation path) between the source and site varied with the location of the hypocenter.

These studies were conducted on individual earthquake records with different hypocenter locations. When assuming a large source area such as an inter-plate earthquake, the Green's Function between the source and site can vary even within the same source area. Petukhin et al. [9] examined the spatial distribution of the Green's Function in the assumed source area for the Nankai Trough Earthquake, and they indicated that the amplitude of the Green's Function becomes large even for distant source areas. Petukhin et al. [9] examined the spatial distribution in the source area using the maximum velocity of the Green's Function as an index. Based on the studies mentioned above [5-8], the maximum velocity and duration of a specific period were found to be different from the maximum velocity distribution of the entire period.

This study investigated the region where the ground motion becomes strong within the source area of the huge earthquake along the Sagami Trough. We focused on the long-period ground motion of cities where high-rise buildings are concentrated, such as Shinjuku (Tokyo Pref.), Marunouchi (Tokyo Pref.), and Chiba (Chiba Pref.). We used the maximum velocity response and input energy of the SDOF models for long-period buildings as an index of the strength of ground motions. The final goal of this study was to show the positional relationship between the area and the SMGA used in the previous damage estimation. In addition, the response values using various periods and damping SDOF models are calculated, and they were found to be dependent on the vibration characteristics of the building.

## 2. Methods

Numerical analysis was performed using the finite difference method (FDM) [10] for a three-dimensional ground model. Although this study focuses on one site, it was necessary to calculate the Green's Function for more than 10,000 subfaults. As calculations using the normal FDM need to be performed for the total number of subfaults, we reduced the computational cost using the reciprocity theorem [8]. In particular, the apparent hypocenter was set at the site; each wave field of the two horizontal (north / east) and vertical impulsive single


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forces and distortion at the real epicenter were calculated. Based on the distortion tensor, we could obtain the Green's Function to represent the displacement at the target site using the impulsive moment tensor at each subfault. Therefore, when the reciprocity theorem is used, the Green's Function can be calculated by a total of three calculations using the FDM for two horizontal and vertical single forces.

In this study, a Japan integrated velocity structure model (JIVSM) [11], which is used for long-period ground motion hazard maps, was used. In a previous study [12], the authors also used this model, and they confirmed that the distance attenuation characteristics of the long-period ground motions from the epicenter to central Tokyo correspond to observation records and numerical analysis results for some earthquakes. Fig. 2 shows the bedrock depth of this model. The Kanto Plain has a seismic bedrock depth of about 3 km over a wide area, and it has a basin structure. The outline of the basin edge is indicated by the dashed line.

Fig. 3 shows the subfault in the source area. First, the subfault location was found from the upper surface of the Philippine Sea plate of JIVSM. In particular, because an inter-plate earthquake is assumed, the area where the upper crust exists and the upper surface of the Philippine Sea plate is less than 55 km or less is used. The target area was divided by a 2 km mesh, and the subfault was set. The depth limit corresponded to the deepest value of the inter-plate earthquake that occurs along the Sagami Trough, which is the basis for setting the previous ground motion prediction [3]. The strike and dip were calculated from the shape of the Philippine Sea plate, and the rake angles were assumed to be 0° and 90°. The source time function was set to be triangular (the rise time of 2 s), and the seismic moment was set to $10^{18}$ Nm. However, because the variation in ground motion based on the source location is discussed in this paper, the seismic moment and the source time function were set only for the convenience of the analysis. Fig. 3 shows the hypocenter distance of each subfault from Shinjuku; the area with the shortest hypocenter distance is slightly south of the Shinjuku point.

The conditions of the FDM are described. For the discretization of space and time, the space step was set to 200 m and the time step was set to 0.01 s. The minimum period that could be referenced by this simulation was 2 s. The edge of the ground model showed a non-reflection boundary [13] and an absorption boundary of 20 grids [14]. The reference period of the inelastic damping was 2 s.

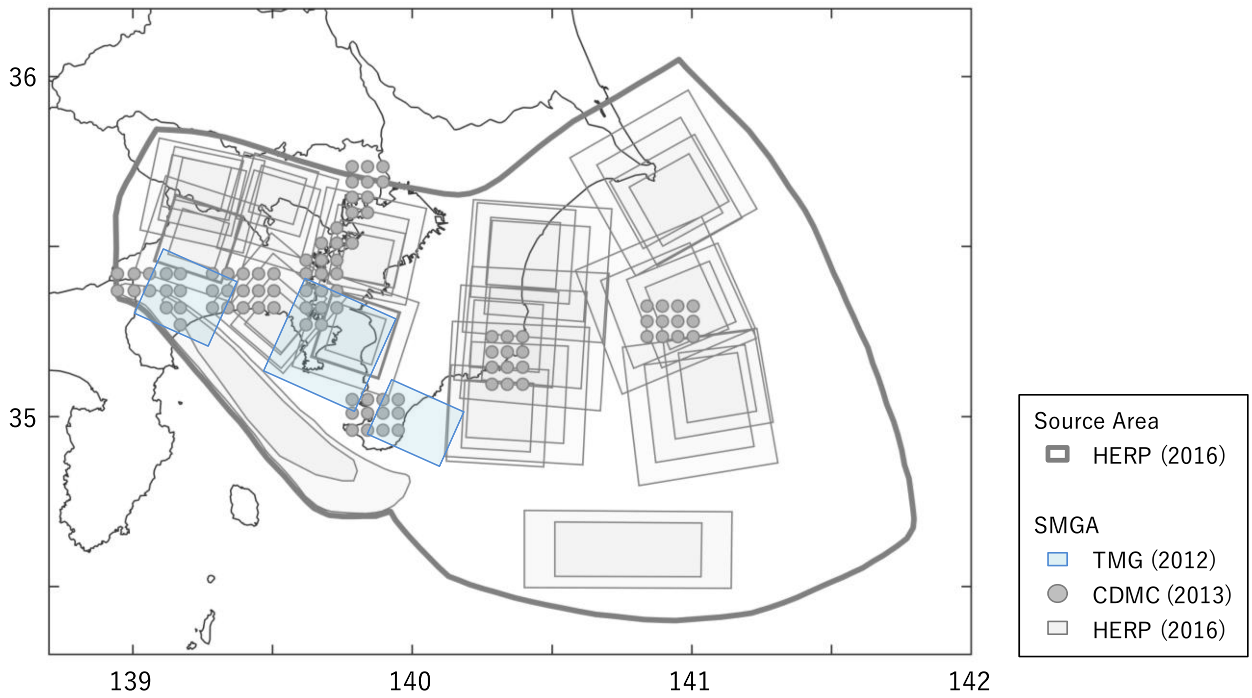


Fig. 1 – Past source models for the Kanto earthquake. HERP (2016) considered uncertainty of the position of the SMGA, and overwrote all cases here.



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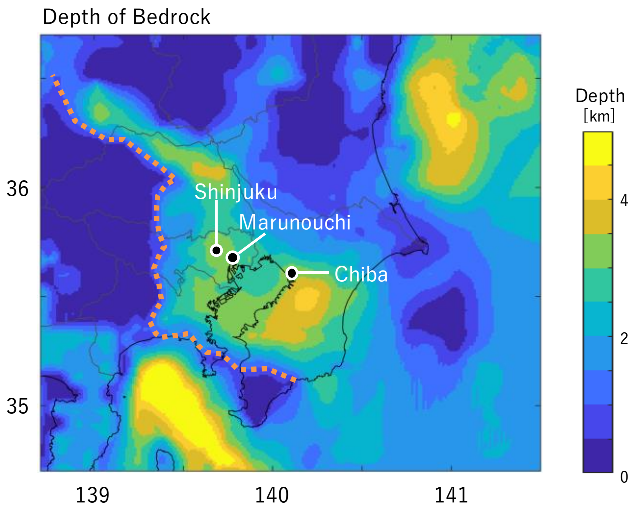


Fig. 2 –Seismic bedrock depth distribution of Japan integrated velocity structure model (JIVSM) used for the finite difference method (FDM). The dashed line indicates the outline of the basin edge of the Kanto Plain.

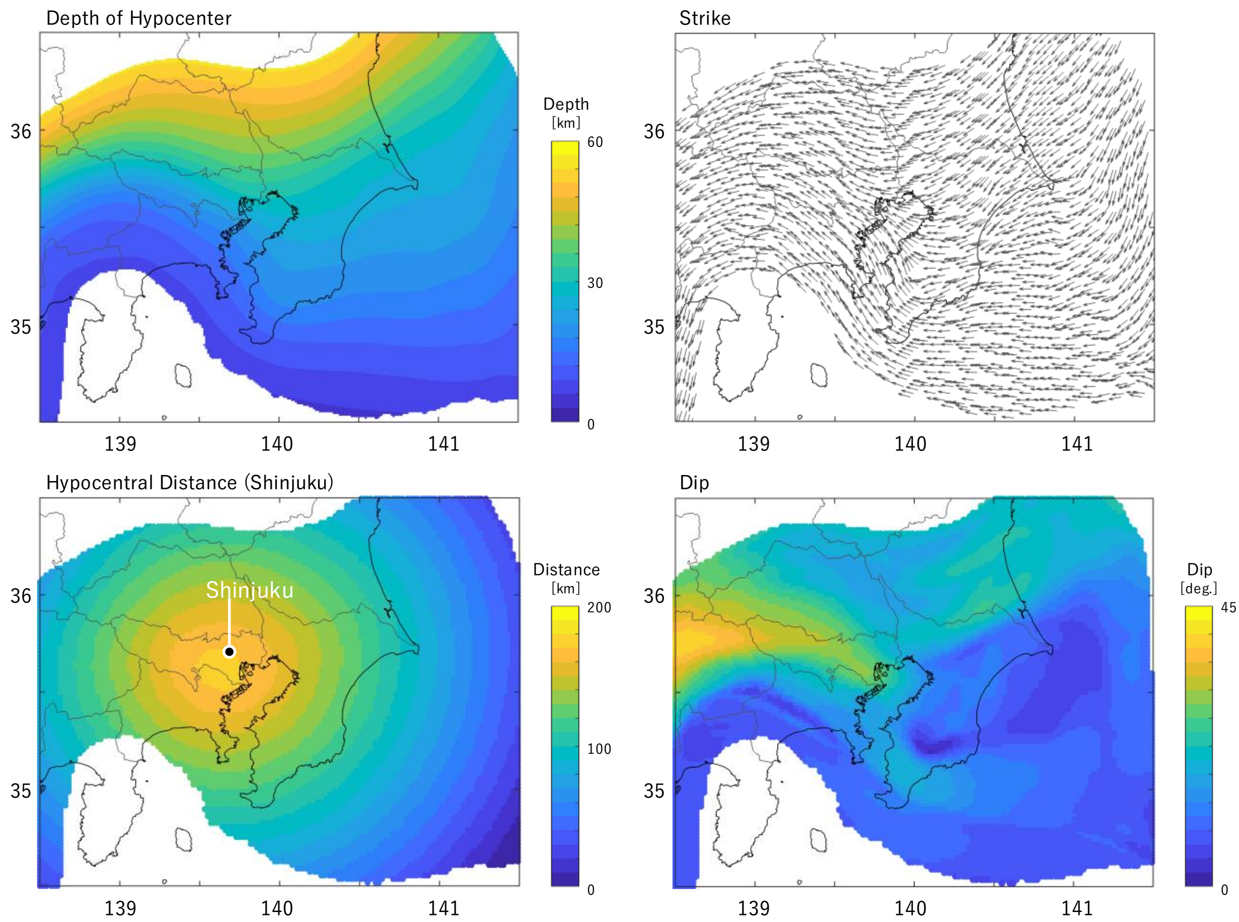


Fig. 3 –Conditions of subfault set based on the shape of the Philippine Sea plate. The hypocenter depth (upper left), strike (upper right), and dip (lower right) are shown. The hypocenter distance to Shinjuku site (lower left) is also shown.



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## 3. Results

In this section, we show the fundamental results about spatial distribution of the Green's function at Shinjuku point first. In sequence, we compare spatial distributions using the result at Shinjuku, Marunouchi and Chiba. Fig. 4 shows the spatial distribution of the response values of the SDOF calculated from the Green's Function assuming a rake angle of 0° at Shinjuku. These response values are velocity response spectra $S_V$ indicating instantaneous maximum amplitude and an energy spectrum $V_E$ indicating amplitude and duration. Fig. 5 also shows the results assuming a rake angle of 90°. We calculated the geometric mean value for periods of 3-5 s for general high-rise buildings and seismic isolation buildings; for periods of 5-7 s assumed for buildings with especially long periods, the damping was set to 5%.

In Figs. 4 and 5, areas 1 to 4 show response values that are dominant, and the distance attenuation of the response values do not always correspond to an increase in the hypocenter distance. Naturally, the response values tend to be large in area 1 near the site, but the response values may be large in areas 2 to 4, which are distant from the site. Focusing on the relationship between hypocenter depth and response values, the values are large at south and west of Shinjuku (area 2 to 4), where the source is shallow. The tendency is remarkable in $V_E$ including the information of duration. This tendency is because surface waves, which are the main components of long-period ground motions, are easily excited. This corresponds to our previous study [15] in which the variation of long-period ground motion tended to appear at a shallow source compared to a deep source. In areas 2 to 4 to the south and west, the spatial distribution of the response values corresponds to the shape of south and west basin edge of the Kanto Plain. In the Kanto Plain, it is known that surface waves are excited when seismic waves enter the plain from the western basin edge and propagate so as to concentrate toward central Tokyo [16, 17]. In contrast, in the northwest to southeast, the response is smaller than that in other directions, and the long-period components affecting long-period structures are small.

Next, the differences in response value types, wave orientations at site, and rake angle of subfault are examined for Figs. 4 and 5. We compared the spatial distribution of $S_V$ and $V_E$ in the same periods and same orientation, which indicated that there are cases with a difference in their spatial distributions. In the period of 3–5 s and the radial component shown in Fig. 4, the difference in amplitude between areas 1, 2, and 4 is as small as $S_V$, but area 4 is as large as $V_E$. Further, the same tendency is seen in the transverse components for the 5–7 s period in Fig. 4, and area 1 has the largest as $S_V$, while area 3 has the largest as $V_E$.

Comparing wave orientations at the site in the same periods, there are dominant areas which have different and common orientations. At the source immediately below the site, its radiation characteristics of the source are deeply shown, and the direction in which large amplitude in the radial and the transverse component is orthogonal, is common near the site. In contrast, at a source far from the site, in the radial component, the amplitude tends to be large in the region from southwest to south (areas 3, 4); however, in the transverse component, the amplitude tends to be large in the west region (area 2). The amplitude in UD component is small but similar to the tendency of radial component, and thus, the amplitude tends to be large in areas 3 and 4.

Comparing the rake angles of the subfault, we found that if the rake angle changes, the basic tendency, in which the amplitude in the south and west is large, is common; however, it is different in the same period. In particular, area 4 tends to be large for a rake angle of 0° in the radial component, but area 3 tends to be large for a rake angle of 90°. A similar tendency is seen in the UD component, indicating that the characteristics are because of the Rayleigh wave, and its excitation differ depending on the rake angle of the source.

Fig. 6 shows a comparison of spatial distribution focusing on the building period and damping case; period of 3-5 s; damping constant 5% assuming damping building, period of 3-5 s; damping constant 20% assuming seismic isolation building, period of 5-7 s; damping constant 2% assuming super high-rise building. Note that RotD100 [18] was used because we did not assume the building orientation. Fig. 6 shows the result about rake angle of 0°. The comparison of the damping constants for the period of 3–5 s (damping building and seismic isolation building) indicates that there is a difference in the absolute value; however, the regions where the amplitude is large are similar. In contrast, a comparison of period bands (damping building and



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super high-rise building) indicates that the characteristics of spatial distribution are slightly different from each other. In particular, in the period of 3–5 s at rake angle of 0°, area 4 has large amplitude in the wide area; however, in the period of 5–7 s, it is not larger than other areas. Further, for area 2, the maximum region in the area is slightly different. Thus, it was found that the difference due to the period was larger than that caused by the damping constant.

Fig. 7 shows a comparison of spatial distribution focusing on the site cases Shinjuku, Marunouchi, and Chiba. We used RotD100 and the result about rake angle of 0°. In Fig. 7, areas 1 to 5 are indicated by broken line circles as areas where the amplitude is dominant. Area 1 is an area where the distance is close to each site and the amplitude is dominant, and shows unique location for each site. In contrast, areas 2 to 5 show common location for each site. Comparing the sites, we found that the area where the amplitude is dominant varies depending on the site. Shinjuku and Marunouchi sites, which are relatively close (less than 10 km), have almost the same spatial distribution, but there is a difference in the relationship between areas 2 and 4. Further, at Chiba, which is far from these two sites, the amplitude is dominant in the area 5, where no dominance was observed at other sites.

Fig. 8 shows areas 1 to 5, where the amplitude is likely to be large and SMGA distributions of previous ground motion predictions by the Government, Japan. Table 1 shows the correspondence between areas 1 to 5 and the SMGA arrangement. Table 1 shows the level of overlapped areas 1 to 5 and the SMGA arrangement as three levels (small, medium, and large). For HERP (2016), the case that the SMGA is arranged shallower (case P1), the case that the SMGA is arranged deeper (case P2), and the case that two SMGAs are arranged immediately below Tokyo and Kanagawa (case P3) were overwritten in Fig. 8. It seems that the assumed source of the past could cover area 1 to 4; however, it can be seen that none of no cases were located in areas 1 to 4. Furthermore, it was found that the assumed source of the past could not cover area 5. As cases in which multiple areas can be considered in one case, case P3 of HERP (2016) is assigned to areas 1 and 3, and case P1 is assigned to areas 2 and 4. It seems that case P3 could cover areas 1 to 5 at most.

## 4. Discussion

This paper focused on long-period ground motion of cities where high-rise buildings are concentrated, such as Shinjuku (Tokyo Pref.), Marunouchi (Tokyo Pref.) and Chiba (Chiba Pref.). The purpose of this study was to investigate areas where ground motions are strong within the assumed source area of the Sagami Trough Earthquake. The final goal was to show the positional relationship between those areas and SMGAs used in previous predictions. It was found that in addition to the area with the short distance (area 1), the response value was large in the area where the hypocenter depth from the south to the west was shallow (areas 2 to 5). Further, comparing with the position of SMGA used in the previous study, there was a partly corresponding area; however, no SMGA was arranged on areas 1 to 5 in one case. Source models including the SMGAs compared in this study, are widely used in the practice of structural design for long-period architectures. It is possible to realize a safer design for buildings with high importance for disaster prevention by modifying the position of SMGA using the results of this study.

The relationship between the response values of areas 1 to 5, the type of response values ($S_V$, $V_E$), the period and damping constants of the SDOF model for general buildings, and sites, was investigated. Therefore, it is important to prepare in advance a spatial distribution of the response value in the assumed source area for a general type of buildings, such as high-rise buildings or seismic isolated buildings.

Moreover, in this paper, only the spatial distribution of the response values of the Green's Function was calculated, as it is actually necessary to consider the SMGA size and the rupture propagation process, which is a future subject. However, even if such points are considered, the result of the seismic simulation naturally becomes large for an area with a large Green's Function. In addition, the area where the amplitude tends to be large may change depending on the accuracy of the ground structure model used for simulation, and it is an issue to confirm the correspondence with the actual observation record. Based on observation records, there are almost no earthquakes with a large magnitude in the areas 1 to 5. However, referring to the results of this paper, it is possible to predict ground motions larger than those predicted by conventional thinking, thus it has



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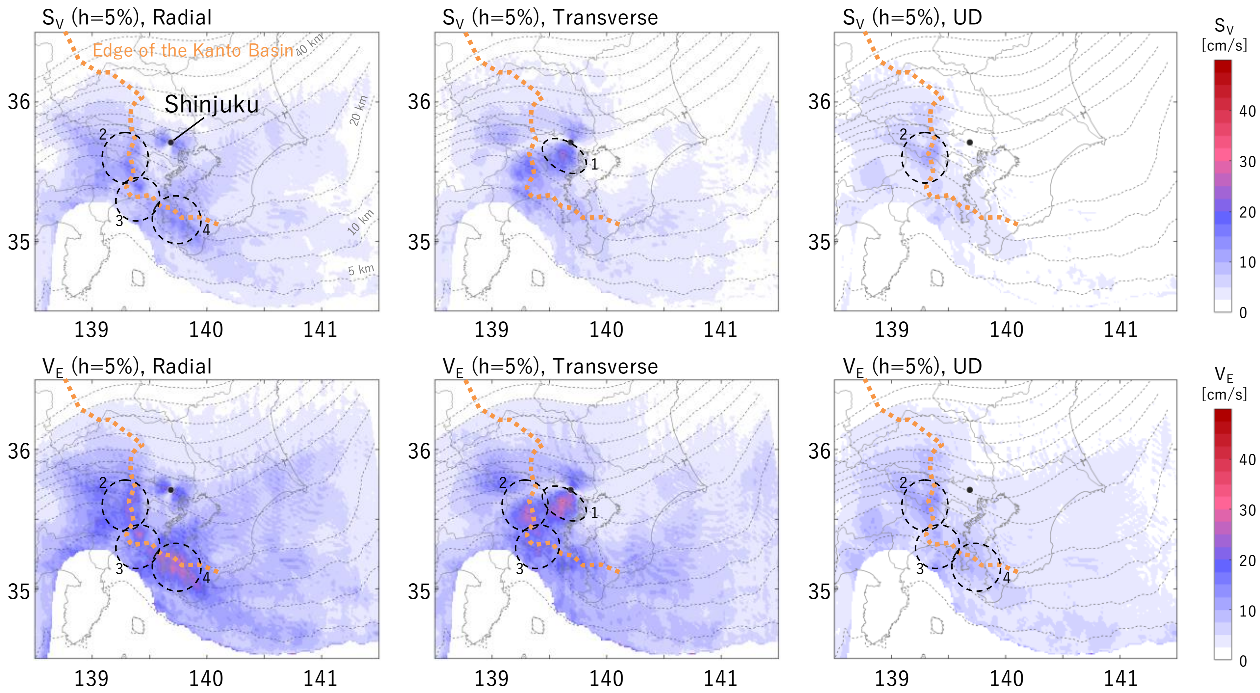
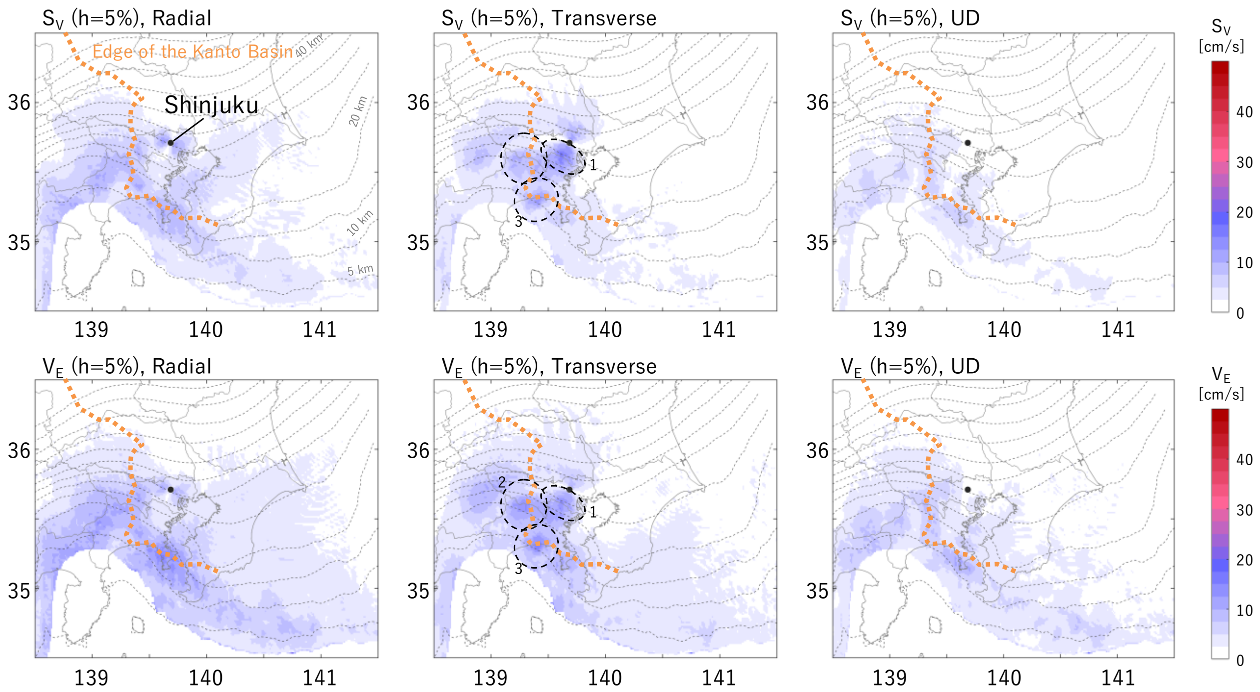



Geometric mean value with a period of 3–5 s




Geometric mean value with a period of 5–7 s

Fig. 4 – Results for rake angle of 0°; the damping constant was set to 5%.



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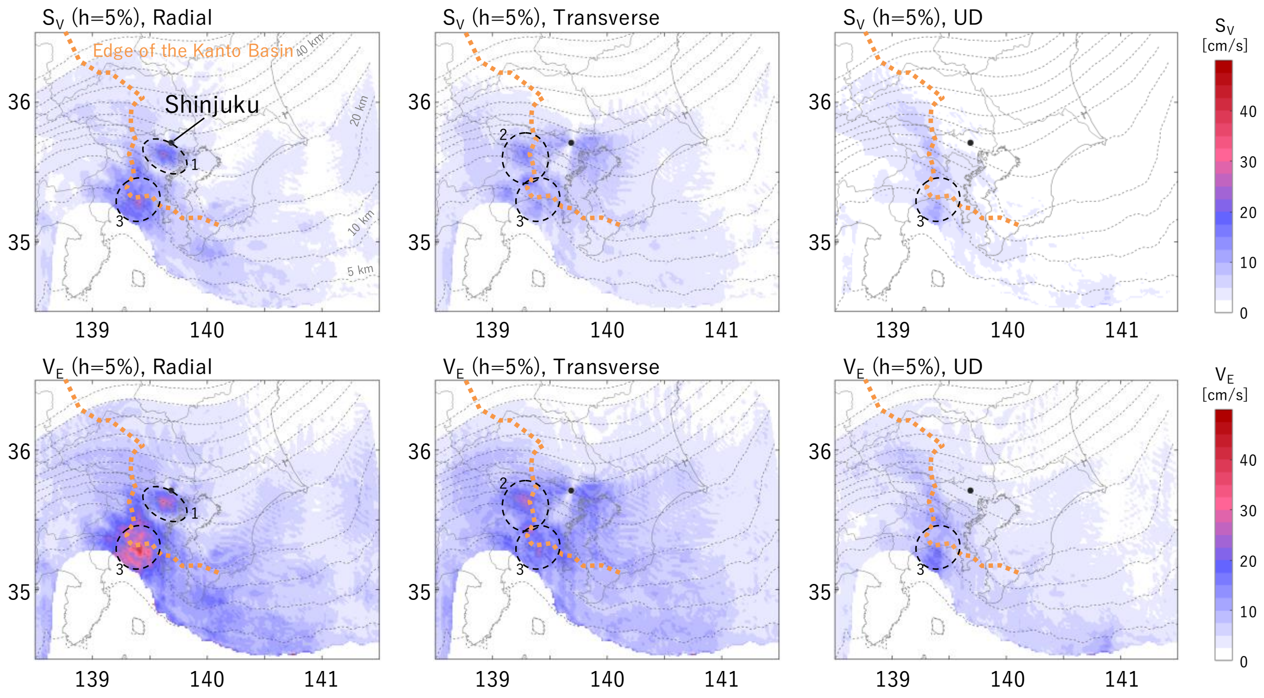
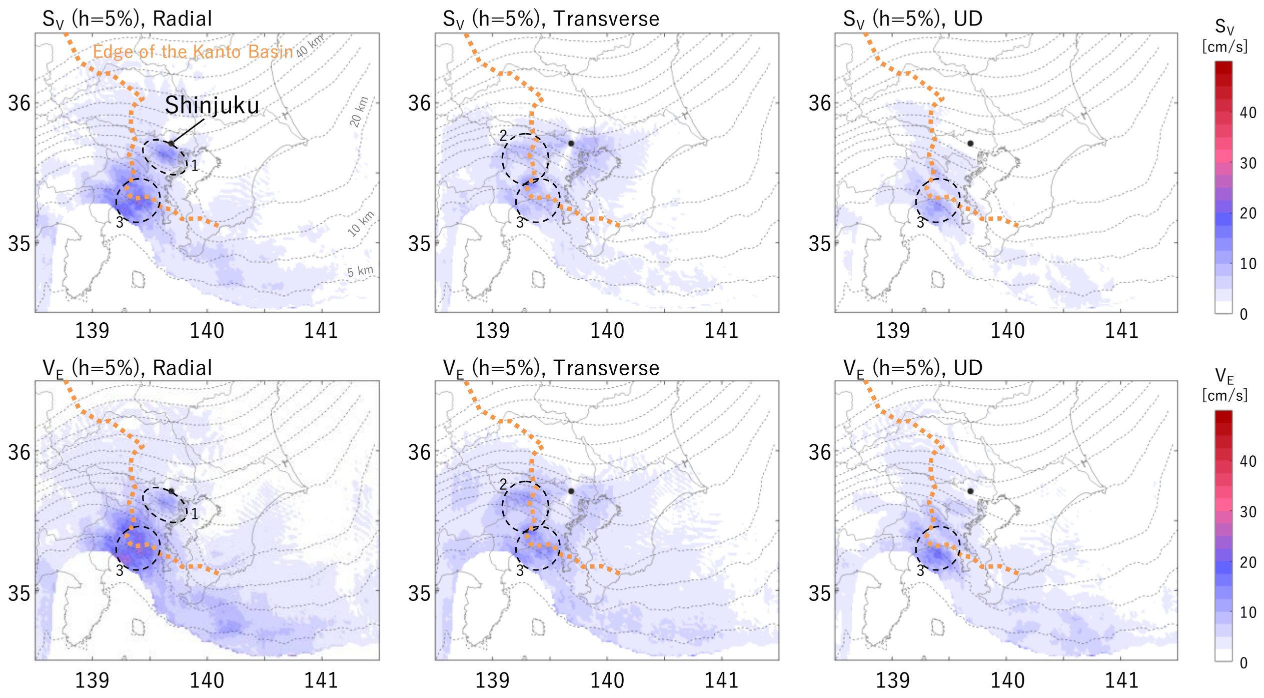



Geometric mean value with a period of 3–5 s




Geometric mean value with a period of 5–7 s

Fig. 5 – Results for a rake angle of 0°; the damping constant was set to 5%.



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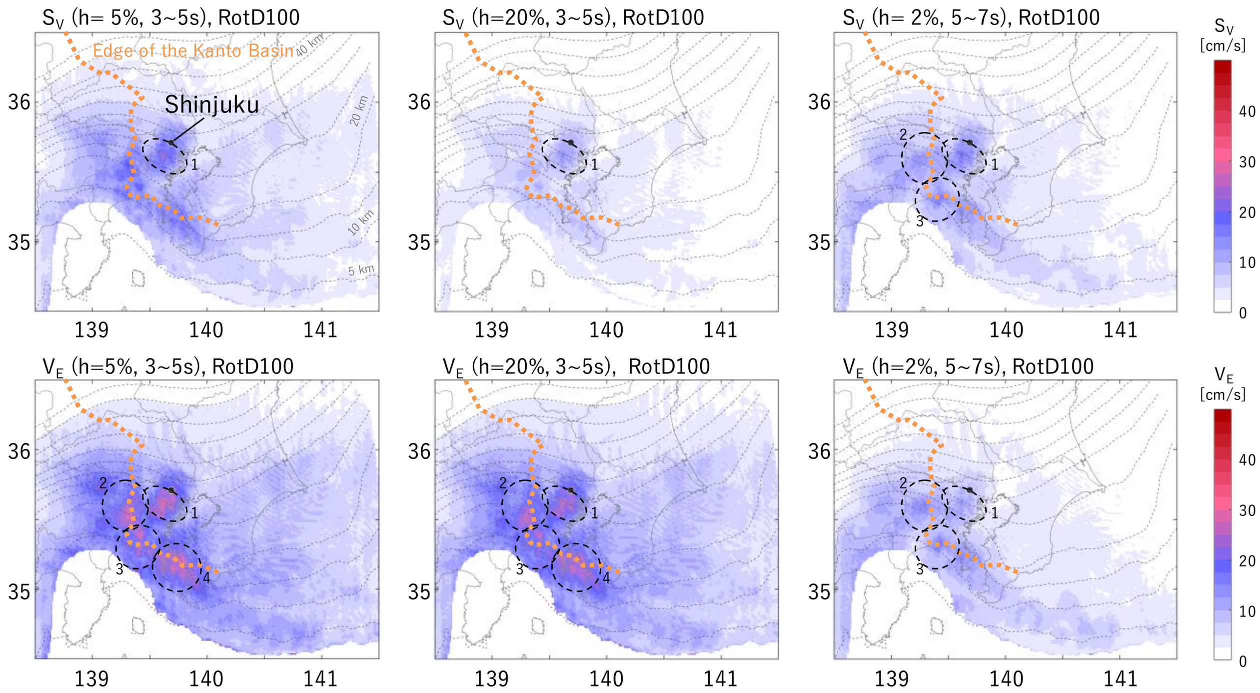


Fig. 6 – Difference per building type. From left: Damping building (3-5 s, h = 5%), seismic isolated building (3-5 s, h = 20%), and super high-rise building (5 – 7 s, h = 2%). The value to plot is RotD100. Results of rake angle 0° are shown.

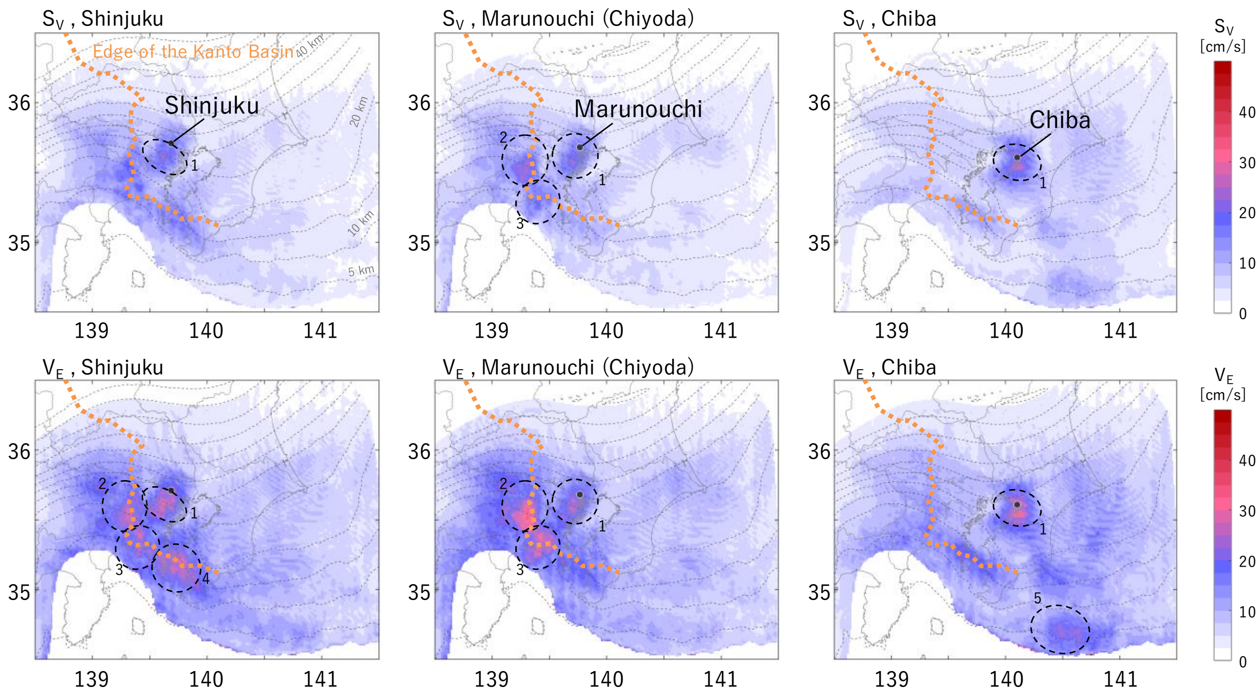


Fig. 7 – Difference per city. From left: Shinjuku City, Marunouchi, Chiba City. The value to plot is RotD100. Results of rake angle 0°.



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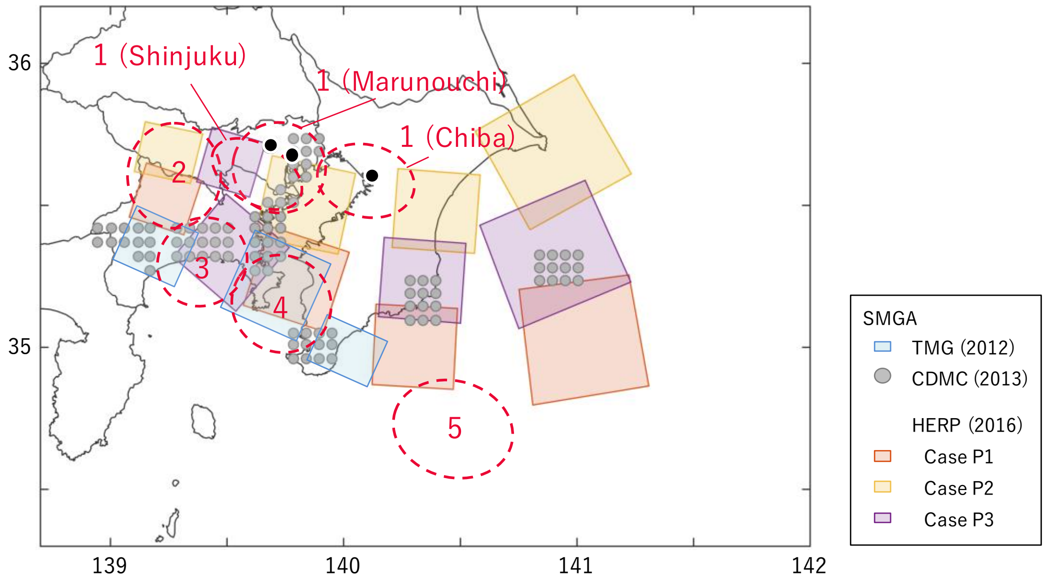


Fig. 8 –Comparison of the SMGA arrangement used in previous ground motion predictions and areas 1 to 5, whose amplitude is dominant in this study. For HERP (2016), three characteristic cases are plotted.

Table 1 –Correspondence between areas 1 to 5 and SMGA used in previous ground motion predictions.

| Area | Level of overlap | | | | |
|---|---|---|---|---|---|
| | TMG | CDMC | HERP P1 | HERP P2 | HERP P3 |
| Area 1 of Shinjuku | - | Small | - | Medium | Medium |
| Area 1 of Marunouchi | - | Medium | - | Medium | Small |
| Area 1 of Chiba | - | Small | - | - | - |
| Area 2 | Small | - | Medium | Medium | Small |
| Area 3 | Small | Medium | - | - | Large |
| Area 4 | Large | Small | Large | - | Small |
| Area 5 | - | - | Small | - | - |

engineering significance.

This study compared spatial distribution focusing on the site cases; Shinjuku, Marunouchi, and Chiba. We found that the area where the amplitude is dominant varies depending on the site. In large cities with many long-period structures (in addition to Shinjuku, Marunouchi, and Chiba, which were the subject of this study, Yokohama, Osaka, Nagoya, etc.), checking in advance where the SMGA has a large effect for buildings, can make the ground motion prediction efficient and safer. In this study, a subduction-zone earthquake was considered as an example; however, the propagation path characteristics of a long active fault may vary within the same fault plane.



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## 5. Conclusions

The spatial distribution of the response value of long-period ground motion in the assumed source area of an inter-plate earthquake along the Sagami Trough was investigated at cities where high-rise buildings are concentrated, such as Shinjuku (Tokyo Pref.), Marunouchi (Tokyo Pref.) and Chiba (Chiba Pref.). As a result, we found the area close to the site (area 1) and the area where the subfault depth was shallow areas 2 to 5. For areas 2 to 4, the spatial distribution of the response value corresponded to the shape of the western and southern basin edge of the Kanto Plain. According to previous studies, the reason that relates such characteristics related to surface waves, which are the main component of long-period ground motions, was guessed. In contrast, from the northwest to the southeast, the response value was small even at the hypocenter distance equal to areas 2 to 4.

The difference in the spatial distribution between the response value type, wave orientation, and rake angle was studied. Thus, it was found that any of the areas 1 to 4 showed large response value, and that the relation of these values was different.

The relationship between the spatial distribution of response value and the building period and damping constant for the SDOF model, were discussed. We compared response value ($S_V$, $V_E$) of three types of buildings, period of 3-5 s; damping constant 5% assuming damping building, period of 3-5 s; damping constant 20% assuming seismic isolation building, and period of 5-7 s; damping constant 2% assuming super high-rise building. As a result, it was found that the difference caused by the period was larger than the difference due to the damping constant.

In addition, the comparison of the spatial distribution focusing on the site case Shinjuku, Marunouchi, and Chiba, were investigated. Comparing the sites, we found that the area where the amplitude is dominant varies depending on the site. Shinjuku and Marunouchi sites, which are relatively close (less than 10 km), have almost the same spatial distribution, but there is a difference in the relationship between areas 2 and 4. Furthermore, at Chiba, which is far from these two sites, the amplitude is dominant in the area 5, where no dominance was observed at other sites.

Moreover, compared to areas 1 to 5 where the response value tended to be large and the SMGA location was used in the previous study, it seems that the assumed source of the past could cover areas 1 to 4; however, it can be seen that no cases were located in areas 1 to 4. Further, it was found that the assumed source of the past could not cover area 5. As cases in which multiple areas can be considered as one case, case P3 of HERP (2016) was assigned to areas 1 and 3, and case P1 was assigned to areas 2 and 4. It seems that case P3 could cover areas 1 to 5 at most.

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