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CHARACTERISTICS OF FAR FIELD SEISMIC INTENSITY DISTRIBUTION FOR THE 1855 ANSEI-EDO EARTHQUAKE

R. Nakamura(1), K. Satake(2), T. Ishibe(3), A. Nishiyama(4), J. Muragishi(5)

(1) *Project researcher, Earthquake Research Institute, The University of Tokyo, naka@eri.u-tokyo.ac.jp*
(2) *Professor (Full), Earthquake Research Institute, The University of Tokyo, satake@eri.u-tokyo.ac.jp*
(3) *Senior researcher, Association for the Development of Earthquake Prediction, ishibe@erc.adep.or.jp*
(4) *Professor (Assistant), Earthquake Research Institute, The University of Tokyo, akihito@eri.u-tokyo.ac.jp*
(5) *Lecturer (part-time), Taisho University, j.muragishi@gmail.com*

Abstract

The 1855 Ansei-Edo earthquake occurred on November 11and caused severe damage in Tokyo (formerly Edo) and the surrounding region with more than 7,000 casualties. The damage was well documented in historical literature and the seismic intensity distribution has been estimated. The Kanto district, where the Tokyo Metropolitan area is located, is situated in a complex tectonic environment due to the subduction of two oceanic plates beneath it; the Philippine plate (PHS) and Pacific plate (PAC) subduct from the south and east, respectively. The complex tectonics and heterogeneity of underground seismic attenuation structures means that the type of earthquake that occurred is still being debated; suggestions include a shallow crustal earthquake to a deep intra-slab earthquake within the PAC. The characteristics of the distribution of seismic intensity and the structure of subsurface seismic attenuations should be considered to estimate the hypocenter of the earthquake reliably.

In this study, we compared the simulated felt area with that estimated from historical documents. We simulated the distribution of the seismic intensity of the 1855 Ansei-Edo earthquake at the far field (approximately 200–500 km from Edo) assuming that seismic intensity is controlled by body waves and using the stochastic Green's function to consider the 3D attenuation structure. We adopted three source models for the 1855 earthquake among those proposed by previous studies. Of these, two were modeled as an intra-slab earthquake within the PHS while the other was an inter-plate earthquake between PHS and PAC.

Comparison of the simulated felt area with observations indicates that the spatial extent of the felt area can be roughly explained by all three source models. This means that the seismic intensity distribution at the far field can be explained by a deeper earthquake, assuming that the intensity is controlled by body waves.

Keywords: 1855 Ansei-Edo earthquake; Historical documents; Seismic intensity; Attenuation structure

1. Introduction

The Kanto region, where the Tokyo Metropolitan area is located, is seismically active and tectonically complicated due to the subductions of two oceanic plates beneath the Okhotsk plate (OKH); the Pacific plate (PAC) and Philippine Sea plate (PHS) subduct from the east and south, respectively beneath the Okhotsk plate (OKH) ([1]; Fig. 1). This region has historically suffered from numerous damaging earthquakes [2] that have been classified as (a) shallow crustal earthquakes, (b) intra-slab earthquakes within the PHS, (c) intra-slab earthquakes within the PAC, (d) inter-plate earthquakes between the OKH and the PHS, (e) inter-plate earthquakes between the OKH and the PAC, and (f) inter-slab earthquakes between the PHS and the PAC.

Among them, the largest earthquakes in this region are the Kanto earthquakes (magnitude (M) ~8) between the OKH and the PHS. The most recent Kanto earthquake (M7.9) of September 1st, 1923 resulted in 105,000 fatalities mostly due to the massive fire [3]. The penultimate Kanto earthquake in 1703 also caused severe damage (>10,000 casualties) in Edo, currently Tokyo city. A recent paleo-seismological study indicated that the antepenultimate Kanto earthquake occurred in 1293 [4], while the 1495 Meio earthquake was also suggested to be possible Kanto earthquake based on deposits at the archaeological site and historical documents [5], [6].

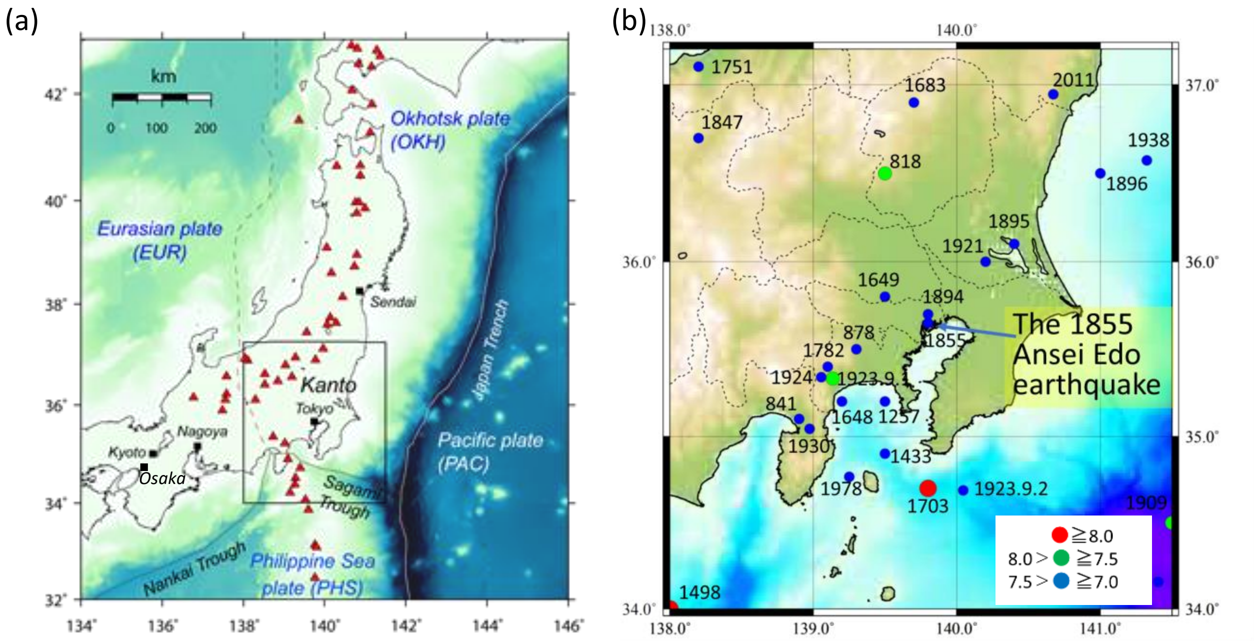


Fig. 1 (a) Tectonic setting and (b) destructive earthquakes in the Kanto region.

The probability of occurrence of the other types of earthquakes with M~7 is equally high; Earthquake Research Committee [7] calculated the probability of occurrence in the next 30 years as 70 %, based on the historical record of M~7 earthquakes occurring between the 1703 and 1923 Kanto earthquakes. The 1855 Ansei-Edo earthquake (hereafter referred as the 1855 earthquake) is one such M~7 earthquake that occurred on November 11th causing severe damage in Edo and the surrounding region with >7,000 casualties. The damage was well documented in historical literature and the seismic intensity distribution has been estimated based on the descriptions (e.g., [8],[9],[10]). However, due to the complex tectonics and heterogeneity of seismic attenuation structure, the type of the 1855 earthquake is still controversial from a shallow crustal earthquake to a deep intra-slab earthquake within the PAC. Consideration should be given to the characteristics of the seismic intensity distributions and attenuation structure to estimate the reliable hypocenter of the earthquake. In this study, we examine the seismic intensity distribution far from the source area, using the body wave calculation method [11], which can estimate far-field seismic ground motions accurately by considering the three dimensional (3D) Qs attenuation structure [12].

2. Previous studies on the 1855 Ansei-Edo earthquake

Many previous studies investigated the hypocenter of the 1855 earthquake, with various estimated depths. This study reviews previous studies investigating the hypocentral depth of the 1855 earthquake and suggests the importance of examining far field seismic intensities. The fundamental data for the 1855 earthquake can be divided into S-P times and seismic intensity distribution, both estimated from historical documents.

A famous kabuki actor, Nakamura Nakazo, left the following description that included P and S-wave arrivals. The description translated from Japanese [13] is as follows: “The strong impact came from the ground. Almost all the women were surprised and screamed. I said, ‘calm down, it’s a big earthquake.’ Omitu said to me ‘you should stand up instead of sitting.’ I stood up. Then the strong shaking started, and I could not walk normally.”

Three studies investigated the hypocentral depth based the above description. Hagiwara [14] estimated the S-P time as approximately 10 s and the hypocentral depth as ~100 km. Nakamura et al. [15] estimated the S-P time as 5–10 s based on the above description and the experiences of others, concluding that the 1855 earthquake was an intra-slab earthquake within the PHS. Usami [16] estimated the S-P time as 3–5 s based on the above description, for which case the depth of the earthquake became shallower than those by other researches.

There are many studies based on seismic intensity distribution. Hikita and Kudo [17] calculated seismic intensity distribution around the Kanto area (within approximately 100 km from the source of the 1855 earthquake) using the empirical Green's function (EGF) [18] and obtained an optimum depth of ~68 km. The depth was near the boundary between the PHS and the PAC. Bakun [19] implied that the 1855 earthquake occurred at the upper surface of the PHS using an attenuation relation that he developed and seismic intensity data within approximately 500 km from the 1855 source. Nakamura et al. [20] [21] obtained 3D-Qs attenuation structure and calculated the seismic intensity distribution within 200 km of the epicenter by using the obtained structure. By comparing the observed and simulated seismic intensity data, they concluded that the 1855 earthquake occurred on or within the PHS. Furumura and Takeuchi [22] used finite difference method (FDM) considering plate structure and compared the characteristics of seismic intensity distribution between observation and calculation within approximately 500 km of epicenter. They suggested that the earthquake was potentially shallow crustal earthquake, because the Lg waves, a guided S-wave in the crust which attenuate less with distance compared to body waves, are effectively excited for a shallow earthquake. The Central Disaster Prevention Council [23] assumed the 1855 hypocenter within the PHS slab at a depth of approximately 40 km. Satoh [24] calculated seismic intensity distribution around the Kanto area (within approximately 100 km from the 1855 source), using EGF and concluded that the 1855 earthquake was an intra-slab earthquake within the PHS.

3. Simulation Method and Verification for Two Moderate Earthquakes

Nakamura et al. [11] developed a method for simulating strong ground motion by combining the stochastic Green's function (SGF), the 3D-Qs attenuation structure (Fig. 2), and the site amplification factor shown in Fig. 3. They successfully reproduced the strong motion records observed within 500 km from the source of the 2003 Tokachi-Oki (M8.0) and 2011 off the Pacific Coast of Tohoku earthquakes (M9.0) (Fig. 4).

The bedrock acceleration spectrum $\alpha^E(f)$ is given by following equation:

$$\alpha^E(f) = Sa^E(f) \cdot Ge \cdot \exp\left\{-\pi \cdot f \cdot \sum \left(T^k / Qs_k(f)\right)\right\} \cdot \sqrt{\rho_1 Vs_1 / \rho_2 Vs_2} \tag{1}$$

where $Sa^E(f)$: Fourier amplitude spectrum of source acceleration, Ge: geometrical spreading factor, $Qs_k(f)$: Qs value in k-th block, T^k: travel time of S-wave through k-th block, and ρ and Vs: density and S-wave velocity, respectively. The subscripts 1 and 2 refer to the element fault and bedrock of the observation point, respectively. By multiplying the appropriate site amplification factor [$g(f)$] with the bedrock acceleration spectrum (i.e., Equation (1)), we can obtain the amplitude spectrum of the target site.

The above 3D-QsSGF method has not been applied to earthquakes on the PHS/PAC plate boundary or within the PHS slab in the Kanto region. This study applies the 3D-QsSGF method to the Kyoshin Network (K-NET) and Kiban Kyoshin network (KiK-net) data from the PHS/PAC boundary earthquake that occurred on 23 July, 2005 (M6.0, h = 78 km) and the intra-PHS earthquake that occurred on 12 September, 2015 (M5.2, h = 57 km). These earthquakes were treated as point sources because of their relatively small magnitudes. We used the F-net moment tensor solutions and assumed stress drop values of $\Delta\sigma = 25$ MPa and $\Delta\sigma = 60$ MPa for the 2005 and 2015 earthquake, respectively. We computed seismic intensity values by converting the calculated amplitude spectrum of 1–10 Hz based on [25], as well as the observed spectrum. To evaluate the effect of the 3D-Qs structure, we also calculated seismic intensity for the uniform-Qs model; $Qs=100f^{0.7}$ [26].

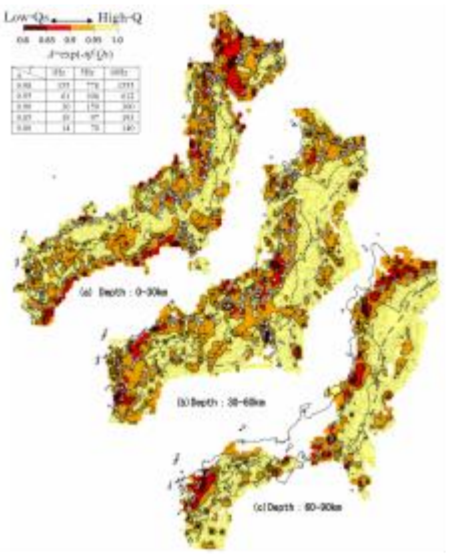


Fig. 2 The three dimensional (3D) Qs Model (example at 10 Hz) for a depth of (a) 0-30 km, (b) 30-60 km, and (c) 60-90 km. [29]

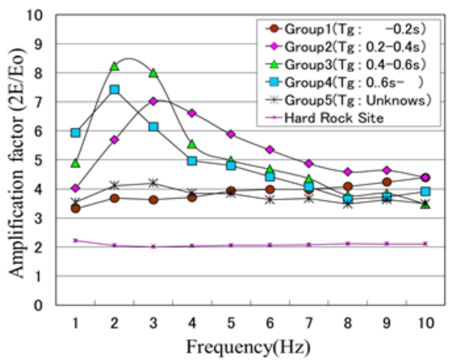


Fig. 3 Frequency-dependent site amplification factor [12]. Groups 1 -4 are classified by the predominant period (Tg) calculated from the logging data, and group 5 denotes unknown Tg. Site amplification factor for the Hard-Rock site is also shown.

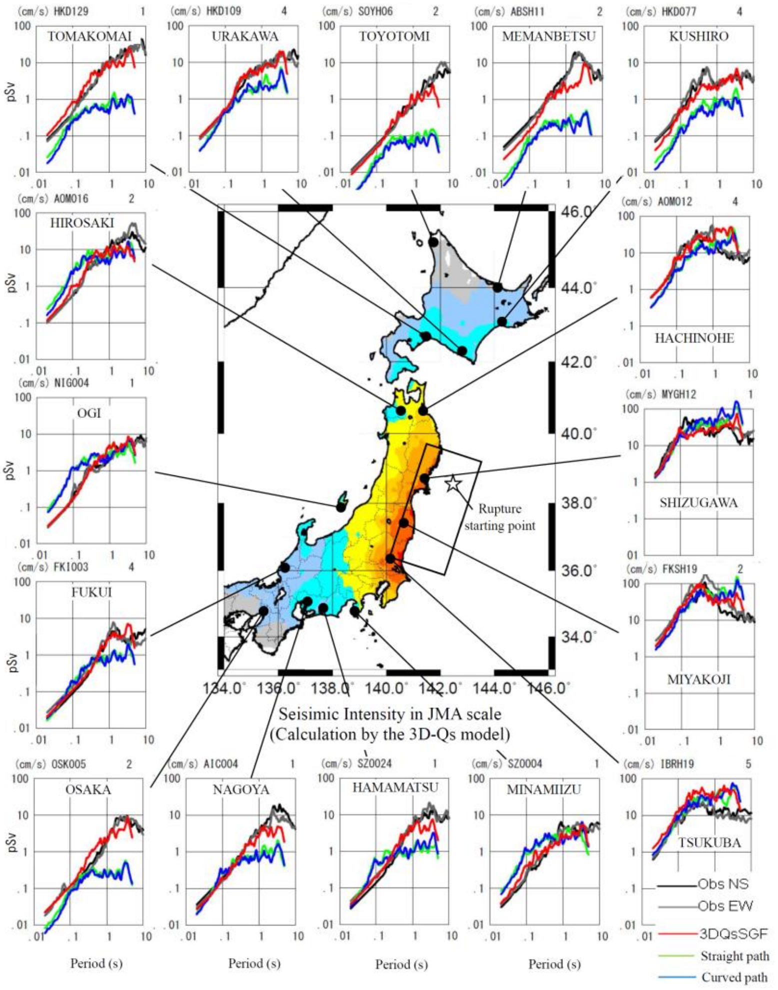
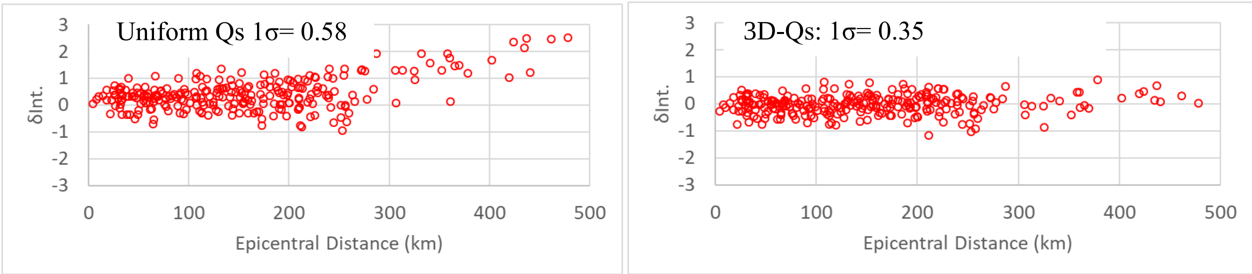
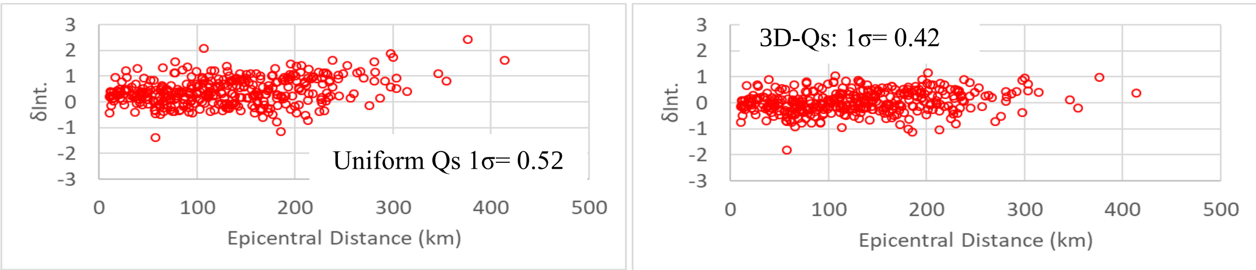


Fig. 4 Comparison of Pseudo-velocity spectrum (pSv, h=5%) between calculations and observation for the 2011 off the Pacific Coast of Tohoku earthquake [11]. Red lines denote the calculations by the 3D-Qs model. Green and blue lines denote the calculations by the uniform-Qs models with straight path and curved path. The numbers in the upper right of each figure denote the classified groups.

Fig. 5 shows the difference between the observed and calculated seismic intensity (ΔInt (O-C)) as a function of epicentral distance. The difference in seismic intensities were smaller for the calculation with the 3D-Qs structure than those for the uniform-Qs. Furthermore, the difference for the uniform-Qs gradually became larger at longer epicentral distances, whereas those for the 3D-Qs structure were small (almost constant) even for longer epicentral distances. Many seismic attenuation relations assume the uniform-Qs structure because they consider a relatively short distance from the source (from 0 to 200 km). As the heterogeneity of the Qs attenuation structure is essential to adequately evaluate long-distance seismic intensities, the 3D-QsSGF method can accurately reproduce seismic intensity for a wide area (up to 500 km).



(a) 2005 earthquake (M6.0, h = 78 km, July 23)



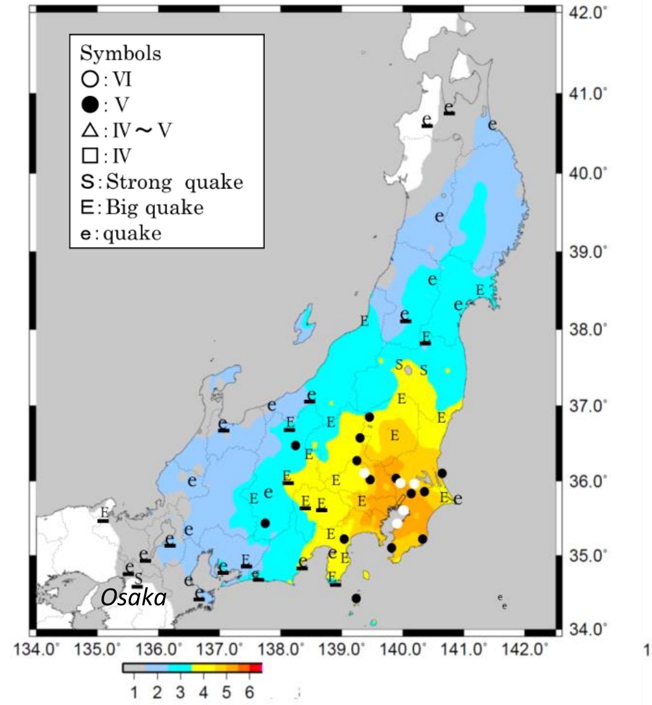
(b) 2015 earthquake (M5.2, h = 57 km, September 12)

Fig. 5 (a) Difference in seismic intensity (ΔInt=O-C) for the 2005 earthquake (M6.0, h = 78 km, July 23) using (left) the uniform Qs and (right) the 3D-Qs structure. (b) Those for the 2015 earthquake (M5.2, h = 57 km, September 12).

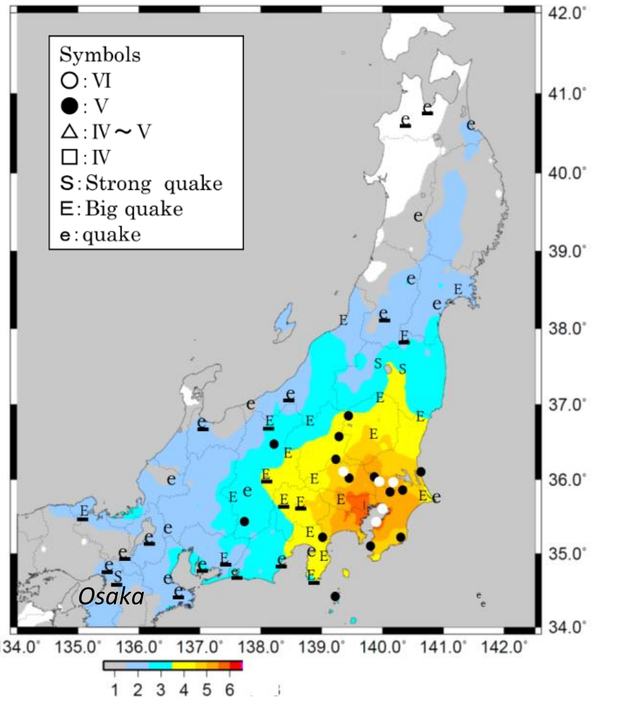
4. Seismic intensity prediction in a wide area of the 1855 Ansei Edo earthquake

Seismic intensities were then calculated in the wide area (up to approximately 500 km) for the 1855 earthquake using the 3D-QsSGF method and the source models proposed by Hikita and Kudo [17], the Central Disaster Prevention Council [23] and Satoh [24]. These models were obtained by using seismic intensity data for the narrower area (up to approximately 100 km), where the heterogeneity of the Qs structure has a smaller influence on seismic intensities than those for longer distance.

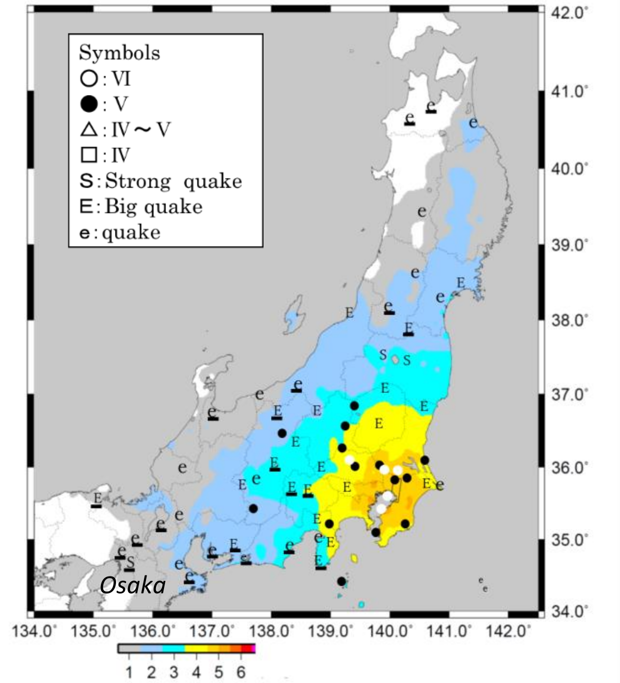
Hikita and Kudo [17] used the K-NET records of the 1998 earthquake beneath Tokyo Bay (M5.1, h = 68 km), which was used as the element earthquake for the EGF method assuming a stress drop of 26 MPa. The Central Disaster Prevention Council [23] assumed a hypocenter within the PHS slab at a depth of approximately 40 km and a fault plane considering the Strong Ground Motion Generation Area (SMGA). The strong ground motion was, for a short period, mainly excited by the SMGA in the simulation; therefore, the calculation was conducted only for the fault parameter values of the SMGA portion. The stress drop was assumed as 52 MPa for the SMGA. Satoh [24] used K-NET, KiK-net and Japanese Meteorological Agency (JMA95) records of the 2005 earthquake in the Chiba prefecture (M 6.0, h = 73 km), which was used as the element earthquake for the EGF method assuming a stress drop of 54.2 MPa for the SMGA.



(a) Hikita and Kudo (2001)



(b) Central Disaster Prevention Council (2013)



(c) Satoh (2016)

Fig. 6 Seismic intensity distribution simulated using the 3D-QsSGF method and source models by (a) Hikita and Kudo [17], (b) The Central Disaster Prevention Council [23], and (c) Satoh [24]. Historical data by Usami et al. [2] are also shown by symbols. Reliable seismic intensity data was underlined for the seismic intensity symbol (e, E or S)

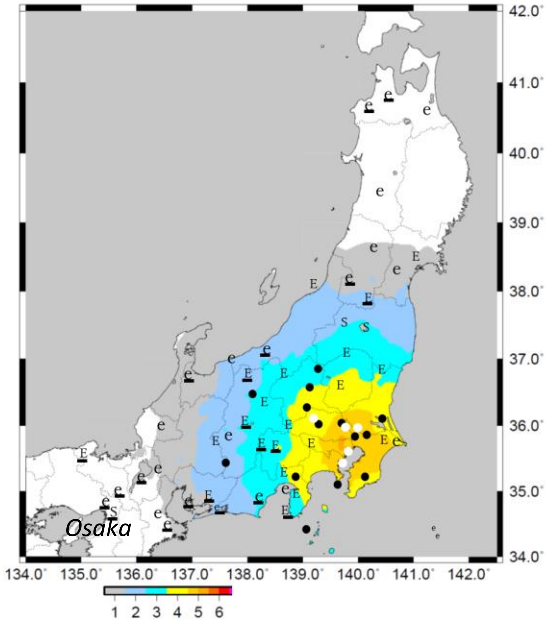


Fig. 7. Simulated seismic intensity distribution using the uniform-Qs structure and source model by Hikita and Kudo [17].

Fig. 6 shows the calculated seismic intensity distribution using the 3D-QsSGF method and the source models proposed by Hikita and Kudo [17], the Central Disaster Prevention Council [23] and Satoh [24]. The seismic intensity values estimated by Usami et al. [2] are also shown by carefully examining the reliabilities of the historical documents. Notably, the historical document of Daimyo (Japanese feudal load), often confuses the recording location, either their territory or Edo.

Fig. 7 shows the simulated seismic intensity distribution using the uniform-Qs structure and source model by Hikita and Kudo [17]. The uniform-Qs structure ($Q = 100f^{0.7}$) poorly explains the felt area, while that simulated from the 3D-Qs structure (Fig. 6a) extends more to southwestern Japan and is fairly consistent with the observation. However, the simulation underestimated the seismic intensity at Osaka, where the documented ground motion was strong.

The Central Disaster Prevention Council [23] and Satoh [24] both assumed the 1855 earthquakes as an intra-slab earthquake within the PHS. The predicted seismic intensity distribution by Satoh's model [24] was slightly smaller than that of the Central Disaster Prevention Council [23]. This difference may be attributed to the seismic moment of Satoh [24] which was 9.37×10^{18} Nm and about one-third of 3×10^{19} Nm of the Central Disaster Prevention Council [23] for the SMGA that caused short-period ground motion. The stress drops for Satoh's [24] model and the Central Disaster Prevention Council [23] were similar at 54.2 and 52 MPa, respectively.

5. Discussion

We simulated seismic intensity from the 1855 earthquake at a long distance (up to 500 km) by a relatively deep earthquake (not within shallow crust) by considering the 3D-Qs attenuation structure. The results imply that the source of the 1855 earthquake did not necessarily have to be in shallow crust to reproduce the seismic intensities for a distant region.

As described in Section 2, Hikita and Kudo [17], Nakamura et al. [21] and Satoh [24], focused on seismic intensity distribution in the Kanto region, whereas Furumura and Takeuchi [22] and Bakun [19] used seismic intensity data for a relatively longer distance (more than 100 km but below 700 km). To explain the seismic intensity at a distant area, Furumura and Takeuchi [18] considered the Lg wave, a guided S-wave in the crust, which attenuates less with distance than body waves.

Bakun [19] used the attenuation relation as shown below:

$$Ijma = -8.33+2.19Mjma-0.00550\Delta h-1.14\log\Delta h \quad (2)$$

where *Ijma* and *Mjma* are seismic intensity and magnitude on the JMA scale, respectively, and *Δh* is epicentral distance in km. We calculated the seismic intensity of the July 23, 2005 earthquake (M 6.0, h = 78 km) at the K-NET and KiK-net stations using this formula. Fig. 8 shows the difference between the observed and calculated seismic intensity (O-C) as a function of hypocentral distance. The calculation underestimated the observation at a short distance (< 100 km), but the difference became smaller at distance between 200–300 km. In Equation (2), the term -1.14 log*Δh* corresponds to a geometric spreading term. To examine this, we converted the coefficient of -1.14 in the JMA seismic intensity to that of peak ground acceleration (PGA). The relation between these can be expressed using Equation (3):

$$Ijma = 2\log PGA+b \quad (3)$$

where *b* is constant. Substituting this relationship into Equation (2) gives:

$$\log PGA = 1.095Mjma-0.00275\Delta h-0.57\log\Delta h-b/2-4.175 \quad (4)$$

Here, the coefficient of geometric spreading term is 0.57. The geometric spreading term is generally 1.0 for body waves and 0.5 for surface waves in the attenuation relationship. The value of 0.57 is close to that of a surface wave.

Both Furumura and Takeuchi [22] and Bakun [19] used the attenuation relation of the surface waves to analyze the intensity at long distance (100–500 km). On the other hand, our study assumes the presence of only body waves. Felt area for the 1855 earthquake can almost be explained by assuming body wave attenuation.

Using historical documents, we can accurately identify the location at which the earthquake was felt, although it may be difficult to determine seismic intensity values from expressions such as “shaking” or “strong shaking.” Usami [27] considered that “strong shaking” corresponds to a seismic intensity of 4 or more on the JMA scale. If it is correct, our prediction is an underestimate. In Osaka, historical documents show “Strong shaking with long duration.” At a far field, extended long duration shaking is sometimes observed by surface wave excitation. Therefore, it is possible that the strong shaking with long duration recorded at Osaka was locally caused by surface waves. To clarify this, modern strong motion records in distant places such as Osaka from earthquakes in Kanto need to be examined.

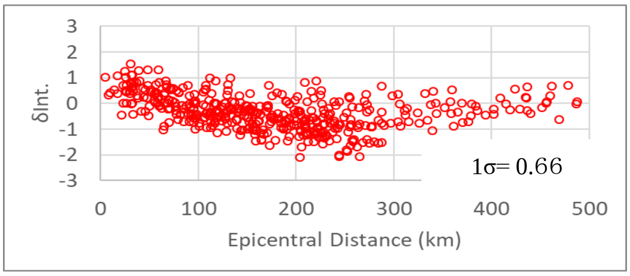


Fig. 8 Difference of seismic intensity (ΔInt=O-C) for the 2005 earthquake (M6.0, h = 78 km, July 23) using the Bakun’s [19] attenuation relation.

6. Concluding Remarks

We simulated the seismic intensity distribution of the 1855 Ansei-Edo earthquake at the far field (approximately 200–500 km from Edo) by assuming that seismic intensity was determined by body waves traveling through a heterogeneous attenuation structure, and compared the simulated felt area with that estimated using historical documents. As a result, the spatial extent of the felt area could be explained roughly by three source models. This means that seismic intensity distribution at the far field could be explained by either a shallow earthquake, if it is assumed that intensity is determined by surface waves, or by a deep earthquake if it is assumed that intensity is determined by body waves. Further investigations are required to highlight the source of the 1855 Ansei-Edo earthquake.

7. Acknowledgements

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