17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

APPLICATION OF A NEW PREDICTION EQUATION OF SEISMIC INTENSITY IN JAPAN TO SOME RECENT EARTHQUAKES

M. Furumura[1] , H. Tanaka[2], R. S. Matsu'ura[3] , A. Noda[4] , and T. Takahama[5]

[1] *Director of Research Division, Earthquake Research Center, Association for the Development of Earthquake Prediction, furumura@erc.adep.or.jp*
[2] *Research Staff, Kozo Keikaku Engineering Inc., hiroto-tanaka@kke.co.jp*
[3] *Senior Research Fellow, Earthquake Research Center, Association for the Development of Earthquake Prediction, matsuura@adep.or.jp*
[4] *Research Fellow, Earthquake and Tsunami Research Division, the National Research Institute for Earth Science and Disaster Resilience, noda@bosai.go.jp*
[5] *Director of Prevention of Disasters Solution, Kozo Keikaku Engineering Inc., takahama@kke.co.jp*

Abstract

A new prediction equation of Japanese instrumental seismic intensities at arbitrary ground places in Japan for Mw 5.4-8.7, and the distances from 10 km to 1000 km was derived by Matsu'ura et al. (2020). The equation has been constructed as a function of moment magnitude (Mw), hypocentral distance, depth of the slab under the site, and V_{S30}. The coefficients for those variables have been obtained for five source types: interplate earthquakes of the Pacific Ocean Plate (PAC), PAC intraplate earthquakes, very shallow crustal earthquakes, shallow intraplate earthquakes of the Philippine Sea Plate (PHS) (hypocentral depth<=50km), and PHS intraplate earthquakes of intermediate depth (depth>50km). Although the equation can be applicable to a wide range of magnitudes and distances, the standard deviations (σ) are 0.5-0.6, which are better than other equations for narrower distance ranges.

Here the prediction equation was applied to two recent earthquakes. One is the 2018 Hokkaido Eastern Iburi earthquake (2018/9/6, Mw6.6). This event occurred at depth of 35 km at the Hidaka collision zone, where the crust is very thick compared to the standard crustal structure in Japan and the seismic velocity structure is very complicated. Instrumental seismic intensities observed at hypocentral distances shorter than about 100 km are close to the calculated one for the PAC intraplate earthquakes, but its attenuation for longer distances is weaker. The weaker attenuation is similar to the equation for PAC interplate earthquakes. The other earthquake is the 2019 earthquake that occurred offshore Yamagata prefecture (2019/6/18, Mw6.4). This earthquake is a shallow crustal earthquake, and the equation for the very shallow crustal earthquakes explain observations well. There are some sites where the observed seismic intensities were considerably larger than the prediction equation, which may be due to the local crustal structure that were not included in the equation.

A comparison of observed seismic intensities with the equation is useful to reveal information about the source type or source characteristics, and about the complex velocity structure of Japan.

Keywords: GMPE; seismic intensity; slab depth under a site; V_{S30}; source type

1. Introduction

Japanese seismic intensities, which have previously judged from human sensations and surveys of the shaking state and damage on structures, have been changed to the instrumental values defined from waveform data recorded by seismographs since 1996 (JMA, 1996[1]). At the same time, the National Research Institute for Earth Science and Disaster Resilience (NIED) has established strong-motion observation networks, K-NET and KiK-net [2]. These stations cover Japan almost every 20 km and many strong-motion data have been obtained by the networks. Matsu'ura et al. (2020) [3] used the NIED data and derived a new prediction equation for the instrumental seismic intensity of Japan (hereafter, MA2020) that can be used for any location in Japan.

Matsu'ura et al. (2020) [3] aims at directly predicting the instrumental seismic intensity on the ground surface. They used about thirty-thousand Japanese instrumental seismic intensities (JISI) calculated from strong motion data recorded at K-NET and KiK-net. Because many earthquakes are concentrated in northern Japan, the data were carefully selected so that some data under such specific conditions are not emphasized. MA2020 was obtained by inverting the seismic intensity data using as few variables as possible for prediction.

Here, we check the validity of MA2020 using seismic intensity data of the 2018 Hokkaido Eastern Iburi earthquake and the 2019 offshore Yamagata Prefecture earthquake.

2. Prediction equation of Japanese instrumental seismic intensities at arbitrary ground sites in Japan, MA2020

MA2020 is a prediction equation of JISI for the following five source types, using the moment magnitude (Mw), hypocentral distance (Δ), S-wave velocity just under the station (V_{S30}), and plate depth under each site (δ). The five source types are interplate earthquakes between the Pacific Ocean Plate (PAC) and the land (type I), intraplate earthquakes in PAC (type II), very shallow crustal earthquakes (type III), intraplate earthquakes in the Philippine Sea Plate (PHS) at shallow depth (<=50km) (type IV), and intraplate earthquakes in the PHS at intermediate depth (>50km) (type V) (Fig. 1).

$$INT(M_{wi}, \Delta_{i,j}, \delta_j, V_{S30j}) = INT_{i,j} = (A_{Ck} + A_{Mk}M_{wi}) - b_k\Delta_{i,j} - \beta_k \log_{10} \Delta_{i,j}$$
$$-d_k \min(\max(\delta_j, \delta_{min})_{i,j}, \delta_{\mathrm{th}}) + G_{VS30\,i,j} \pm \sigma_{i,j}, \qquad (1)$$

where $INT_{i,j}$ is JISI value at the j-th station for the i-th event, M_{wi} is the moment magnitude of the i-th event, $\Delta_{i,j}$ is the hypocentral distance between the i-th hypocenter and the j-th station, and V_{S30j} is the average S-wave velocity at the j-th station, and $\sigma_{i,j}$ is the residual (O-C). δ_j is the PAC or PHS slab depth under the j-th station, and δ_{min} and δ_{th} for the PAC slab are set to 50 km and 250 km, respectively, from the preliminary analysis by Matsu'ura et al. (2020) [3]. The term δ_j is used to explain the abnormal intensity distribution due to the subducting slab. $\{A_{Ck}, A_{Mk}, b_k, \beta_k, d_k\}$ is common for events in the same k-th source type.

$$G_{VS30\,i,j} = \{B_o + B_M(M_{wi} - 7.9)\} \log_{10}\{\min(V_{S30j}, V_{\mathrm{th}})\} \qquad (2)$$

is strongly related to site factor and independent of the source type. B_o is obtained from analysis of a very deep event in the mantle with a hypocentral depth of 680 km, which occurred off the western shore of Ogasawara (Bonin) Islands on May 30, 2015. This is an earthquake with unique conditions such that seismic waves are considered to be incident almost vertically on the Japanese archipelago, and it is convenient to know the site characteristics of each observation point [3].

The obtained parameters of $\{A_{Ck}, A_{Mk}, b_k, \beta_k, d_k, B_o, B_M\}$ in MA2020 are listed in Table 1. These values were derived from earthquakes for Mw 5.4-8.7, distances from 10 km to 1000 km, and stations with V_{S30} from less than 90 to 2200 m/s. The data that does not contain S-waves or their peak ground motion velocity does not reach 0.1 cm/s were excluded from the inversion analysis. The equation has been validated by applying it to nine earthquakes, including the 2016 Kumamoto earthquake [3].

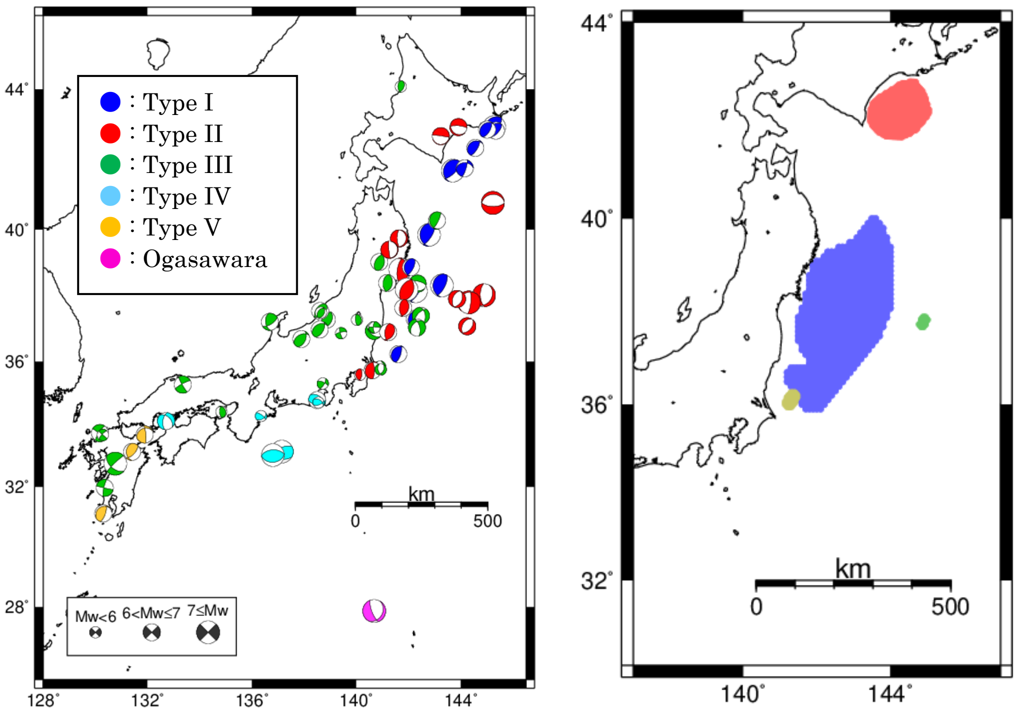


Fig. 1 – Used events for MA2020. Left : Location and mechanism of earthquakes with Mw lower than 7.5. Right : Source area of earthquakes with Mw equal and larger than 7.5 for which the closest distances from each colored source area were used instead of hypocentral distances. [3]

Table 1 – Parameter values of Eqs. 1 and 2 for each source type. *Bo* is fixed by the value determined by the preliminaly analysis for the Ogasawara event. The bar means AIC judged the parameter as unnecessary. [3]

Source Type	Ac	A_M	b $\times 10^{-3}$	β	d $\times 10^{-3}$	B_O	B_M	V_{th}	δ_{min} δ_{th}	σ
I	5.45	1.13	1.80	2.34	4.67				50-250 (km)	0.561
II	4.14	1.80	—	3.55	8.81					0.564
III	3.39	1.38	2.30	2.46	—	*-1.80*	-0.159		—	0.602
IV	3.81	1.43	5.30	2.42	—			1000 (m/s)	—	0.484
V	2.13	2.23	—	3.86	8.93				≥10	0.494
Ogasawara	32.8		—	8.10	9.36	-1.80	—		50-250 (km)	0.519

3. Application to recent earthquakes

3.1 The 2018 Hokkaido Eastern Iburi earthquake

The Hokkaido Eastern Iburi earthquake occurred at 03:07 JST on September 6, 2018 on the west side of the Hidaka Mountains in central Hokkaido. According to the F-net catalog by NIED, the Mw is 6.6, and the hypocentral depth is 35 km. Fig. 2 shows the distribution of instrumental seismic intensities at K-NET and KiK-net stations of the NIED and the GSI Map [6] in the same range.

Similar to the data processing in Matsu'ura et al. (2020) [3], JISIs were calculated from the observed records at the K-NET and KiK-net stations. The JISIs are compared with the prediction equation for type III of MA2020 in Fig. 3. The solid and dashed red line in each graph indicates the MA2020 equation for type III and its standard deviation. As seen in Table 1, MA2020 for type III does not depend on the slab depth, but depends on magnitude, hypocentral distances, and V_{S30}. If we focus on a single earthquake, the type III equation becomes a function of two parameters; the hypocentral distance Δ and the V_{S30} at the observation point. Fig. 3(a) indicates MA2020 for V_{S30}=300m/s compared with JISIs which are adjusted for the difference from the reference V_{S30} (JISI is multiplied by the ratio of 300 m/s and V_{S30} at each site).

The JISIs observed at hypocentral distances beyond 200 km attenuate with respect to the hypocentral distances similar to MA2020. However within a distance of 100 km, the JISI tends to be larger than the equation. In addition, JISIs in the northeastern Japan are large along the Pacific coast, which is similar to the abnormal seismic distribution for interplate or intra-slab earthquakes.

To take into account the abnormal seismic intensity distribution in Fig. 3, we compare the JISIs with MA2020 for type II (Fig. 4) and type I (Fig. 5), which are related to the depth of the subducting slab δ (Table 1).

In Fig. 4, most JISIs at stations with hypocentral distances shorter than 100 km are within the standard deviation. However MA2020 overestimates intensities along the Pacific coast in Hokkaido. It may mean factor *d*, which is related to the term for depth of the PAC slab, is too effective than the observed seismic intensities. If the JISIs are adjusted to V_{S30} of 300m/s and to the hypocentral distances of 100 km, the JISIs are well explained by the MA2020 equation for type II.

A comparison of the JISIs with MA2020 for type I (Fig. 5) shows discrepancy for distances within 100 km, but quite similar tendency for large distances. The residuals for the large distances are smaller than for type III and type II. The abnormal seismic intensity distribution is also explained by the MA2020 model well.

The good agreement between JISI and MA2020 for type II within 100 km may indicate that stress drop of this event was high, or this event radiated strong high-frequency energy, like an intra-slab earthquake. At the source area, the crust is unusually thick (Iwasaki et al., 2019[4]), and heat flow is very low (Tanaka, 2004[5]) in Japan. These geophysical features also suggest that strong high-frequency energy was released from the source.

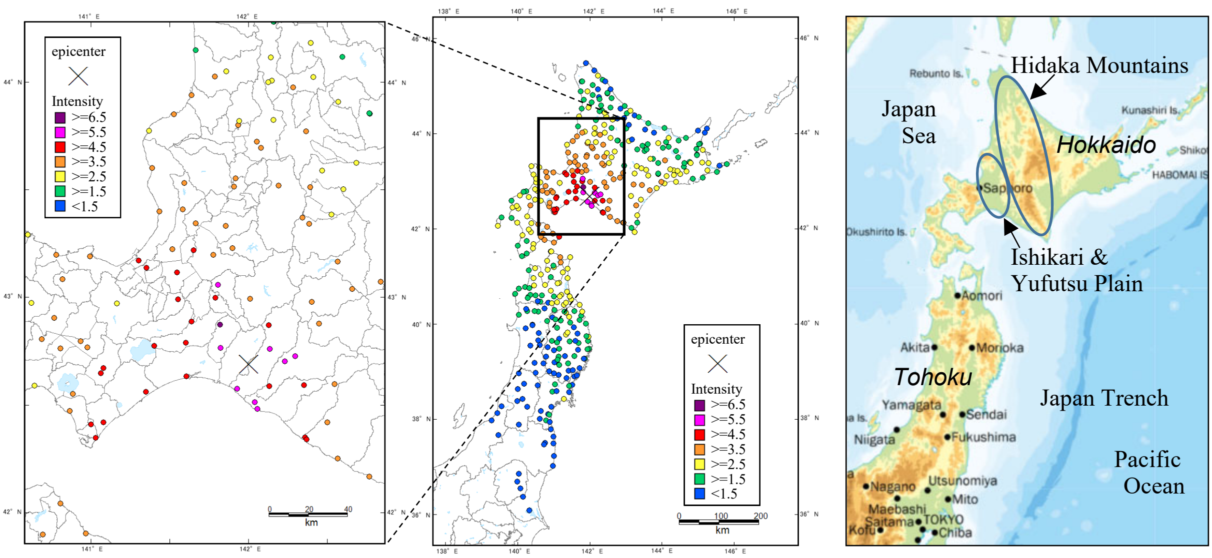


Fig. 2 – Seismic intensity distribution of the Hokkaido Eastern Iburi earthquake (M_W6.6) on September 6, 2018 (left: enlarged view near the epicenter, center: overall map) and the GSI Map [6] showing topography (right).

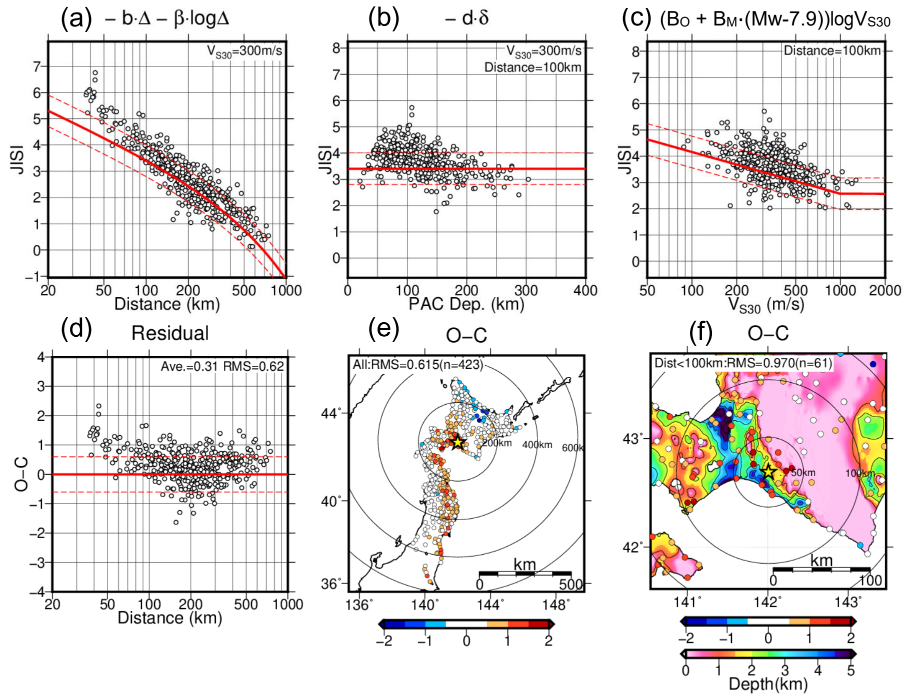


Fig. 3 – Comparison of JISI for the Hokkaido Eastern Iburi earthquake with MA2020 for type III. (a) Relationship between $\varDelta$ and JISI adjusted to reference V_{S30} (=300m/s). (b) Relationship between δ and JISI, adjusted to reference V_{S30} and reference $\varDelta$ (=100 km). (c) Relationship between V_{S30} and JISI adjusted to reference $\varDelta$. (d) Relationship between $\varDelta$ and the residual. (e) Distribution of residual between JISI and seismic intensities calculated by MA2020. (f) Enlarged view of the residual distribution at each station and depth of the Vs2000m/s layer by Yoshida et al.(2007) [7].

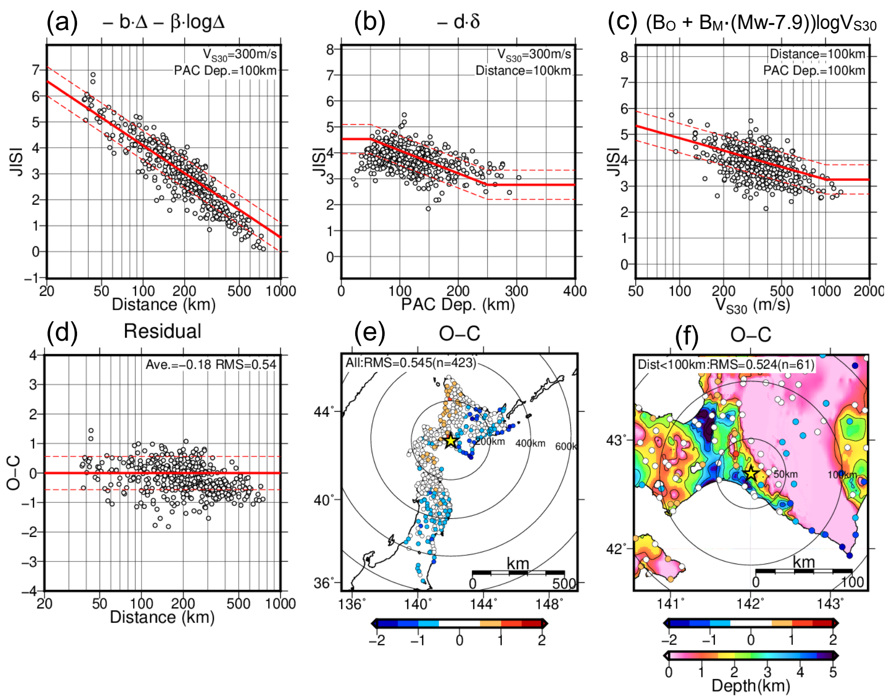


Fig. 4 – Comparison of JISI of the Hokkaido Eastern Iburi earthquake with MA2020 for type II.

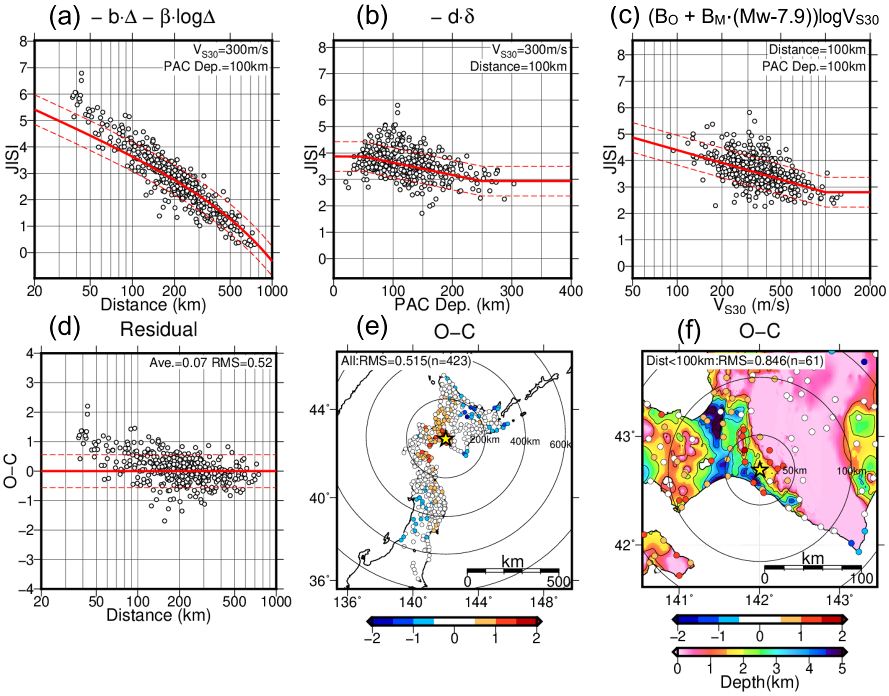


Fig. 5 – Comparison of JISI of the Hokkaido Eastern Iburi earthquake with MA2020 for type I.

In addition, the abnormal distribution of the JISIs and the consistency of JISIs with MA2020 for type I at long distances indicate that attenuation characteristics of observed records are at nearly the same level as the interplate earthquakes. It is well recognized that the abnormal distribution of JISI is caused by the subducting slab of the high-V and high-Q regime. Furumura and Kennett (2005)[8] have shown that the heterogeneous inner structure of the plate generates strong forward scattering of the high-frequency waves and that the slab waveguide effect for selective frequency produces an abnormal intensity distribution.

3.2 The 2019 Offshore Yamagata Prefecture earthquake

On June 18, 2019 at 22:22 JST, an earthquake occurred off the coast of Yamagata Prefecture. According to the F-net catalog, the M_w is 6.4 and the depth of the hypocenter is 11 km. Fig. 6 shows the seismic intensity distribution at K-NET and KiK-net stations of the NIED and the GSI Map [6].

For the offshore Yamagata Prefecture earthquake, JISIs are compared with MA2020 for type III (Fig. 7). The overall seismic intensity attenuation characteristics can be roughly explained by MA2020. However, the JISIs for hypocentral distances of 100 to 200 km are clearly larger than MA2020. Particularly large residuals seem to exist near the prefectural border between Iwate and Akita prefectures on the northeast side of the epicenter. Therefore, we focused on Iwate and Akita prefectures and displayed an enlarged residual distribution in Fig. 8. There is the Kitakami River running from north to south at around 141.2 degrees east longitude, and the age of the bedrock differs greatly between east and west of the Kitakami River. The red upward and blue downward triangles in Fig. 8 indicate JISIs at western and eastern stations of the Kitakami River, respectively. The black circle is for the stations outside of the Iwate and Akita prefectures. It clearly shows that JISIs at the western stations are larger than MA2020 (type III), and that those at eastern stations are at nearly the same level as JISIs at other areas and MA2020.

This suggests that heterogeneous crustal structure greatly affects the JISI distribution for a shallow earthquake such as the offshore Yamagata Prefecture earthquake.

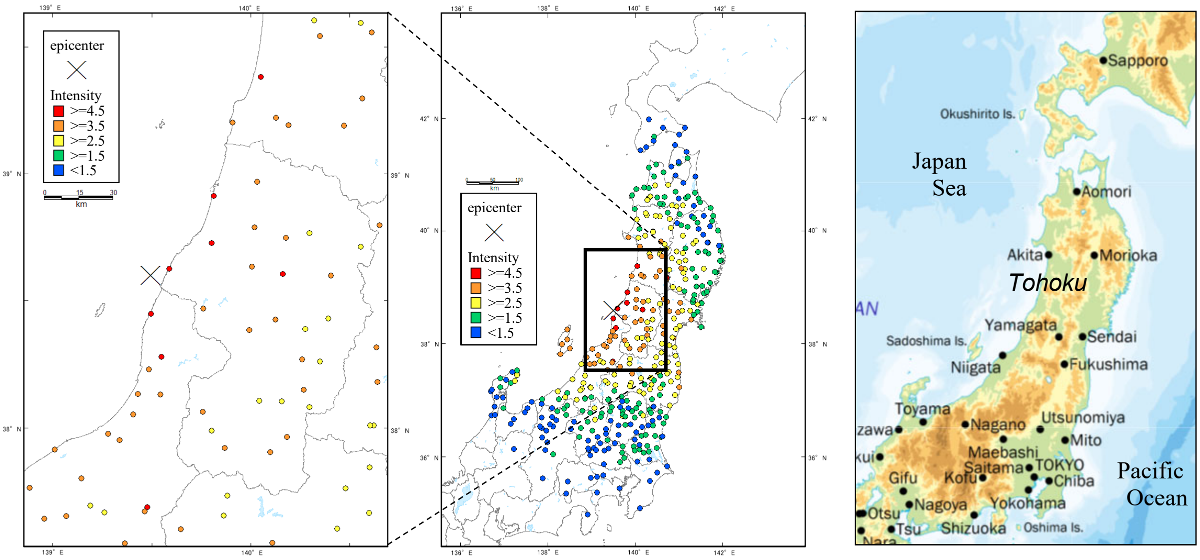


Fig. 6 – Seismic intensity distribution for the earthquake off the coast of Yamagata Prefecture (M_W 6.4) on June 18, 2019 (left: enlarged view near the epicenter, center: overall map) and the GSI Map [6] showing topography.

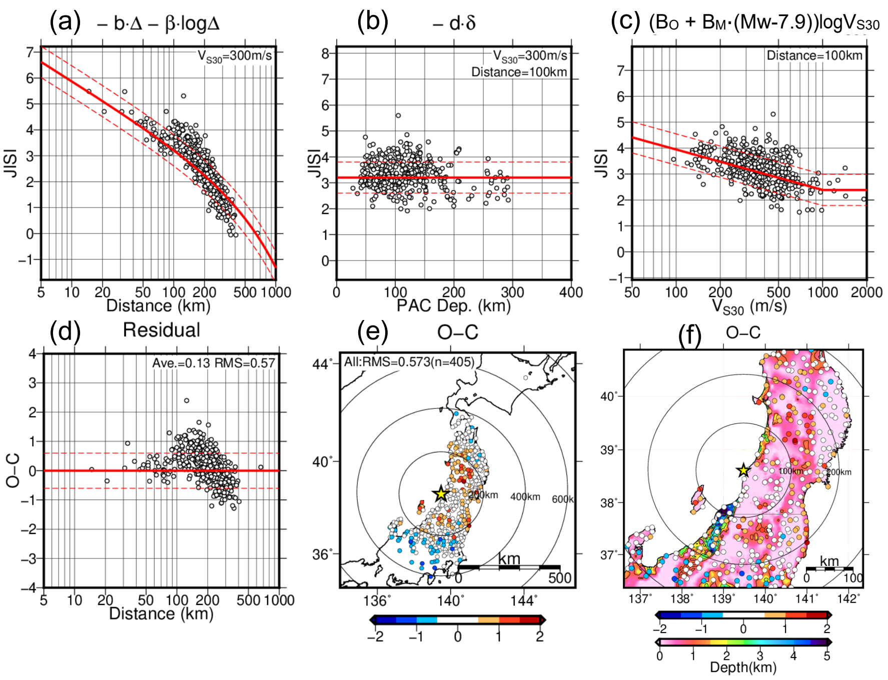


Fig. 7 – Comparison of JISI for the offshore Yamagata earthquake with MA2020 for type III. Enlarged view of the residual distribution in (f) is shown with a depth of the Vs2000m/s layer in the JIVSM model (HERP, 2012[9], Koketsu et al., 2012[10]).

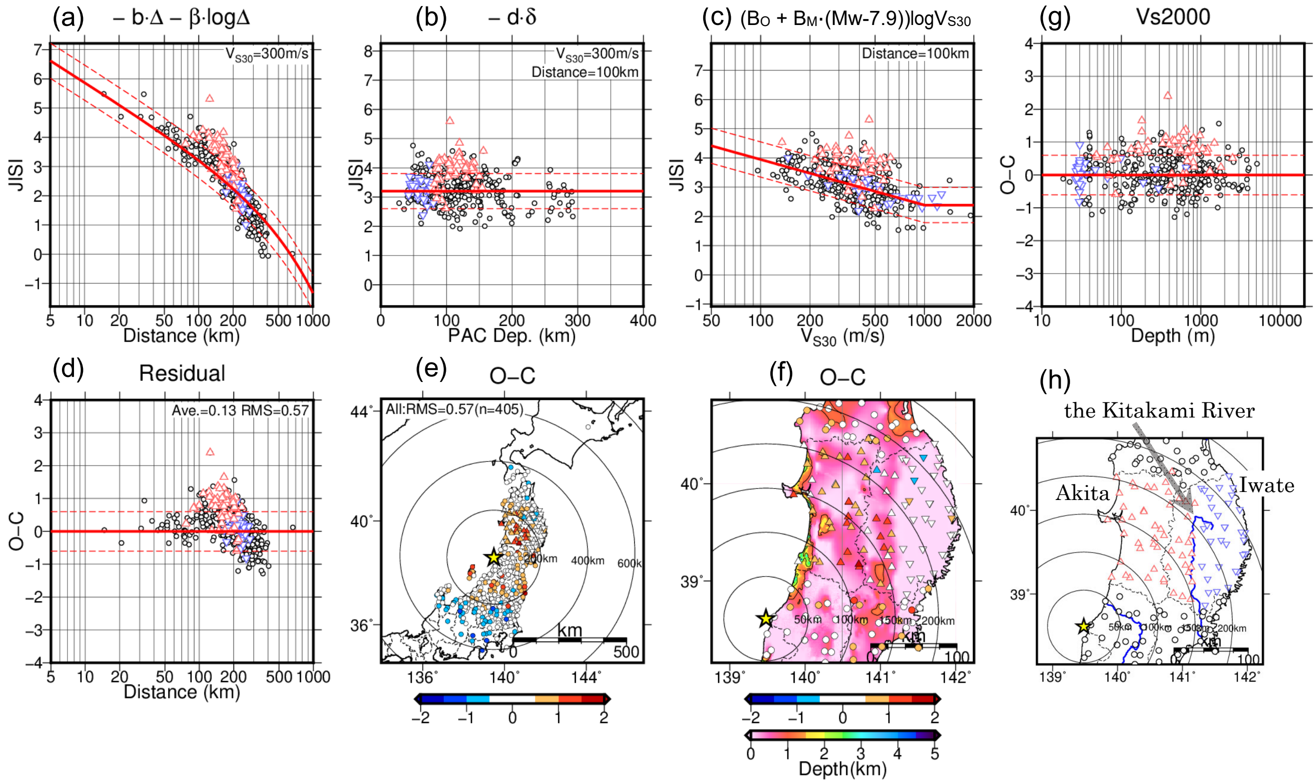


Fig. 8 – Same as Fig. 7 for the left 6 panels ((a) to (f)). The upper and lower right panels ((g) and (h)) display residual versus upper depth of the Vs2000m/s layer, and station distribution, respectively.

4. Discussions

Section 3.1 showed that JISIs of the Hokkaido Eastern Iburi earthquake were consistent with type II MA2020 for the stations within a hypocentral distance of about 100 km. However, large seismic intensities far beyond the standard deviation were observed in some areas. We can also see different residual trends between the Ishikari-Yufutsu Plain, and the Hidaka Mountains on the east side or the mountain area on the west side, which may indicate the effects of deep structure in this area.

To see the distribution and the relation between the JISIs and velocity structure in detail, JISIs within 100 km epicentral distance are plotted with the color scale changed in Fig. 9. The depth and the inclination of the upper surface of the Vs2000m/s layer are also shown in the left and right panels, respectively. These parameters are both smoothed using values in each 10 km square referring to Kamiya et al. (2000) [11].

Fig. 10 shows the results of multiple regressions using the following formula.

$$\text{O-C} = a \cdot \log_{10}(D_{2000}) + b \cdot (1 - \cos(I_{2000})) + c \pm \sigma \qquad (3)$$

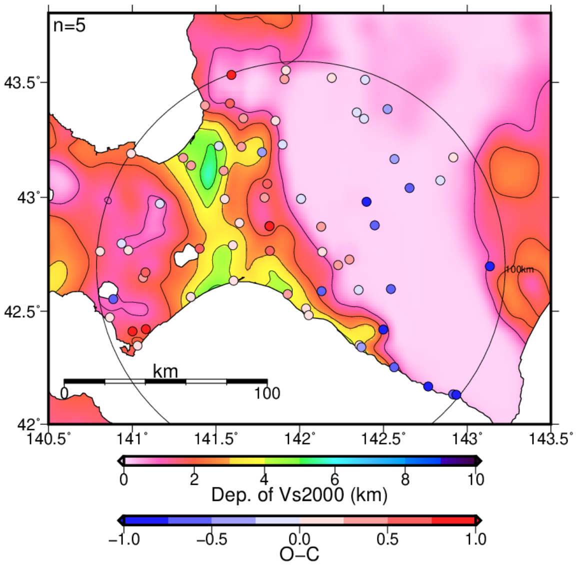
where O-C is the difference between the JISIs and MA2020 (residual) for stations of epicentral distances within 100 km, D_{2000} (m) and I_{2000} (degree) are the depth and inclination of the Vs2000m/s layer upper surface, a and b are the regression coefficients, and σ is the standard deviation. The left panel in Fig. 10 shows the relationship between the upper surface depth D_{2000} and the residuals with a circle, and the inclination I_{2000} is shown in color. The inclination is normalized to 0° in the regression results. The right panel is a diagram in which the relationship between the inclination I_{2000} and the residual is indicated by a circle, and the upper surface depth D_{2000} is indicated by a color. The regression results are normalized to a depth of 500 m. Observed JISI tends to be larger as the upper surface of the Vs2000 layer is deeper and smaller as the inclination is steeper. Therefore, it is considered that there is an effect from deep structures on the residuals, which cannot be removed by the correction of V_{S30}. Relation between JISIs and the depth and the inclination of other layers are also examined but those correlation coefficients are smaller than the case for the Vs2000m/s layer.

Fig. 11 (a) shows the distribution of residuals and the thickness of Green Tuff layer in back arc of the northeastern Japan, which is just above the VS2000m/s layer by Yoshida et al. (2007)[7]. The Green Tuff layer is distributed in the southwestern part of Hokkaido and other part in subsidence area due to the expansion of the Japan Sea, and the thickness of the Green Tuff layer is thought to represent thickness of the soft sedimentary layers. The residuals tend to be positive (observations are larger than MA2020) in areas with the thick Green Tuff layer. Fig. 11 (b) and (c) show the relationship between the residuals with the Green Tuff layer thickness; Fig. 11 (c) is for all stations in Hokkaido, and Fig. 11 (b) is for selected stations close to the source area which are seen in Fig. 11 (a). Similar to the tendency seen in Fig. 11 (a), the residual tends to increase as the Green Tuff layer becomes thicker. In addition, this relationship can be seen for JISIs beyond a certain thickness (about 0.2 to 0.5 km) in Fig. 11 (b) and (c).

5. Summary

A prediction equation of Matsu'ura et al. (2020) for JISIs at any point in Japan was applied to the Hokkaido Eastern Iburi earthquake and the Offshore Yamagata Prefecture earthquake, and the validity of the equations was examined. The Hokkaido Eastern Iburi earthquake was compared with the equations for three source types, and it was clarified that the Hokkaido Eastern Iburi earthquake had intermediate properties between intraplate and interplate earthquakes. In addition, the relationship between the residual of JISIs from MA2020 and the velocity structure was analyzed, and it was shown that there was some relationship between JISIs and the depth and inclination of the upper surface of the Vs2000m/s layer, and between JISIs and the thickness of the Green Tuff layer. The JISIs of the earthquake off the coast of Yamagata Prefecture can be roughly explained by the equation for shallow crust earthquakes, but it is suggested that the JISI is strongly influenced by the heterogeneous crustal structure that cannot be explained by V_{S30}.

MA2020 may provide information on the source type or source characteristics, and the heterogeneity of the velocity structure which affects the instrumental seismic intensities.



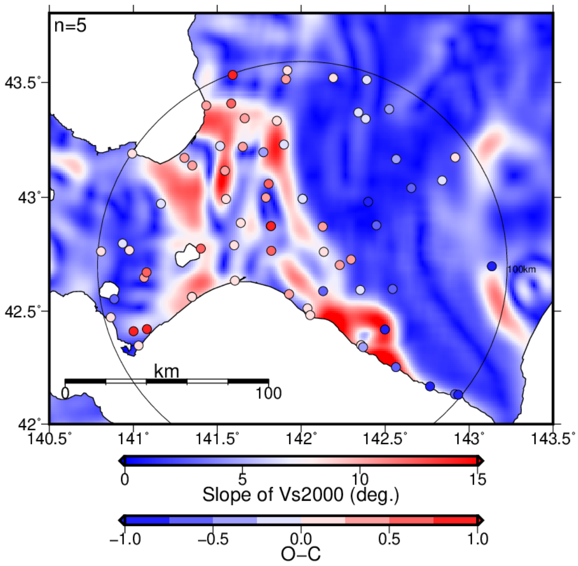


Fig. 9 Left: Depth of the upper surface of Vs2000m/s layer and the residual. Right: Relationship between the inclination of the upper surface of the Vs2000m/s layer and the residual. The color contour of the residual emphasizes the color from Fig. 4. The depth and inclination of the upper surface of the Vs2000m/s layer are smoothed using data in each 10 km square referring to Kamiya et al. (2000) [11].

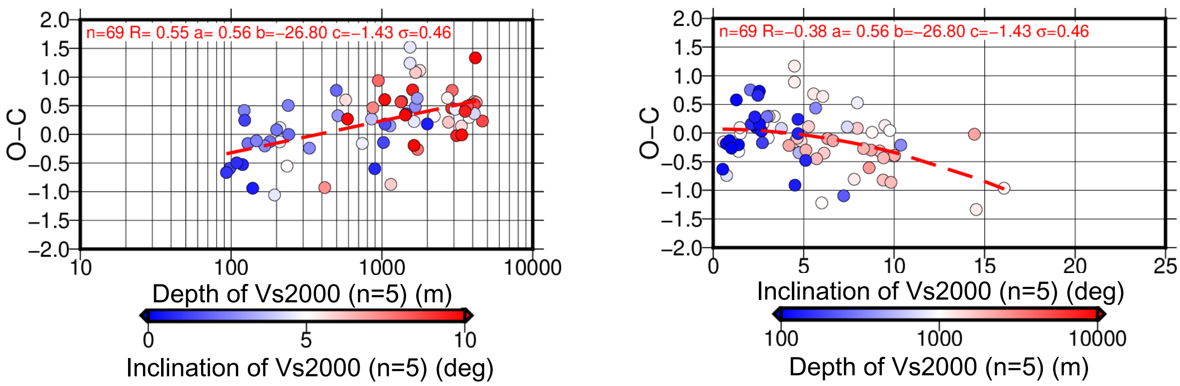


Fig. 10 Left: Relationship between the depth of the upper surface of the Vs2000m/s layer and the residual. Right: Relationship between the inclination of the upper surface of the Vs2000m/s layer and the residual.

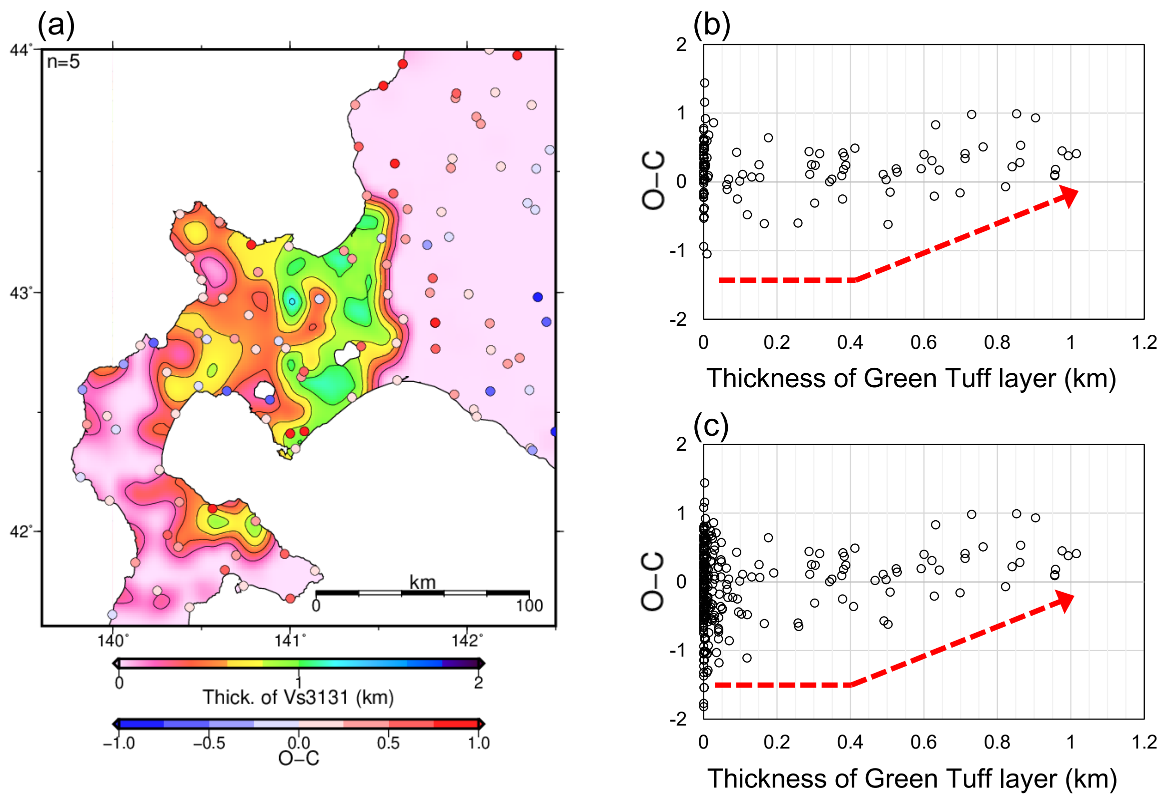


Fig. 11 Residual between JISIs and MA2020. (a) Green Tuff layer thickness and distribution of the residuals. (b) Relationship diagram between Green Tuff layer thickness and the residuals of stations close to the source area which are seen in Fig. 11 (a). (c) Relationship diagram for all stations in Hokkaido.

6. Acknowledgements

We used K-NET, KiK-net and F-net data by National Research Institute for Earth Science and Disaster Resilience. This study was done with funding from the Ministry of Education, Culture, Sports, Science and Technology, Japan for the Headquarters of Earthquake Research Promotion of the Japanese government.

7. References

[1] Japan Meteorological Agency (1996): Notification No. 4 (in Japanese. English version is available at http://www.hp1039.jishin.go.jp/eqchreng/at2-4.htm)

[2] National Research Institute for Earth Science and Disaster Resilience (2019), NIED K-NET, KiK-net, *National Research Institute for Earth Science and Disaster Resilience*, doi:10.17598/NIED.0004.

[3] Matsu'ura, RS, Tanaka H, Furumura M, Takahama T, Noda A (2020): A new prediction equation of instrumental seismic intensity of Japan reflecting source type characteristics. Submitted to *Bulletin of the Seismological Society of America*.

[4] Iwasaki et al. (2019): Structural heterogeneity in and around the fold-and-thrust belt of the Hidaka Collision zone, Hokkaido, Japan and its relationship to the aftershock activity of the 2018 Hokkaido Eastern Iburi Earthquake. *Earth Planets Space*, 71:103, doi:10.1186/s40623-019-1081-z.

[5] Tanaka A (2004) Geothermal gradient and heat flow data in and around Japan (II): Crustal thermal structure and its relationship to seismogenic layer. *Earth Planets Space*, **56**, 1195–1199, doi: 10.1186/BF03353340

[6] GSI Map : Geospatial Information Authority of Japan, https://maps.gsi.go.jp/development/ichiran.html (in Japanese. The English version is available at https://www.gsi.go.jp/ENGLISH/index.html)

[7] Yoshida K, Yoshimi M, Suzuki H, Morino M, Takizawa F, Sekiguchi H, Horikawa H (2007): 3D velocity structure model of the Ishikari and Yufutsu sedimentary basins. *Annual report on active fault and paleoearthquake researches*, **7**, 1-29 (in Japanese with English abstract).

[8] Furumura T, Kennett BLN (2005): Subduction zone guided waves and the heterogeneity structure of the subducted plate: Intensity anomalies in northern Japan. *J. Geophys. Res.*, **110**, 10, doi:10.1029/2004JB003486.

[9] Headquarters of Earthquake Research Promotion (2012): "Long-period ground motion prediction map" 2012 prototype, Data download, (in Japanese). (available at https://www.jishin.go.jp/evaluation/seismic_hazard_map/lpshm/12_choshuki_dat, last accessed on Jan. 24, 2020).

[10] Koketsu K, Miyake H, Suzuki H (2012): Japan integrated velocity structure model Version 1; *15th World Conference on Earthquake Engineering*, pp.4.

[11] Kamiya I, Kuroki T, Tanaka K (2000): Interpretation of Geomorphology and Geology Using Slope Gradation Map. *Geoinformatics*, **11**(1), 11-24, https://doi.org/10.6010/geoinformatics1990.11.1_11 (in Japanese with English abstract).

