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HIGH-FREQUENCY WAVE GENERATION OF THE INTRA-SLAB EARTHQUAKES IN JAPAN

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SUMMARY

The acceleration source spectra were evaluated by eliminating the effects of propagation path and site characteristics from observation records. The target events are intermediate depth earthquakes in the Hokkaido district and the Tohoku district, and intra-slab earthquakes of southwestern Japan. A stress parameter $\Delta\sigma$ was evaluated from the high frequency level M_{HF}, and the relation between $\Delta\sigma$, regionality, focal mechanism, earthquake magnitude and focal depth was examined. As a result, $\Delta\sigma$ of intra-slab earthquakes was not much affected by regionality, mechanism and focal depth, and its earthquake magnitude effect was the largest.

INTRODUCTION

Earthquakes in Japan can be classified into inland earthquakes, interplate earthquakes and intra-slab earthquakes. Among these earthquakes, there has been little investigation on the source characteristics of intra-slab earthquakes.
In this paper, the study region is widened, and the high frequency wave generation is investigated for intra-slab earthquakes occurring throughout Japan. First, as many observation records as possible are collected, and propagation path characteristics and site characteristics are evaluated based on this. Next, the acceleration source spectrum was evaluated by removing those effects from the observation records. Next, the level M_{HF} of the amplitude fixed part of the high frequency region and a stress parameter $\Delta\sigma$ are evaluated from the corner frequency of this spectrum. Finally, the tendency of $\Delta\sigma$ is examined by looking at the difference between regionality, mechanism, earthquake magnitude and focal depth.

DATA

The epicenter of the earthquake discussed herein is shown in Figure 1. The Pacific plate is subducting in the northeastern part of Japan, and the Philippine Sea plate is subducting in the southwestern part. First, a classification will be made into southwestern Japan and northeastern Japan.
It has been pointed out that in the case of intra-slab earthquakes in the subducting Pacific plate, a down dip extension type (DE-type) occurs frequently in the Hokkaido district, and a down dip compression type (DC-type) occurs frequently in the Tohoku district (Kosuga et al. [1]). In this paper, northeastern Japan where Pacific plate is subducting is classified into the Hokkaido distirct and the Tohoku district. In the

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future discussion, propagation path characteristics, site characteristics and source characteristics are evaluated for each of these three regions.

Many intra-slab earthquakes in the Hokkaido district and the Tohoku district occur at a depth of 60km or more. In this study, therefore, in the Hokkaido district, 51 events which occurred at a depth of 50km or more were considered. This also includes interplate earthquakes (Sub-type). At the same time, intra-slab earthquakes were classified into DC-type, DE-type and hinge type (Hin-type). As a result, there were 18 DE-type, 4 Hin-type and 19 Sub-type. The DC-type was not included. Ten earthquakes outside these categories were classified as Other-type. The data set consists of 370 horizontal components recorded at 21 stations: the Meteorological Agency (JMA), the Port and Harbor Research Institute (PHRI) and the Central Research Institute of the Electric Power Industry (CRIEPI).

For intra-slab earthquakes in the Tohoku district, 21 events occurring at a depth of 50km or more were examined. These were classified as 8 DE-type, 6 DC-type, 2 Sub-type and 5 Other-type. The data set consists of 210 horizontal components recorded at 25 stations: JMA, PHRI and KiK-net.

In southwestern Japan, the intra-slab earthquakes occur at shallow location of depth about 40km. Hence, 28 intra-slab earthquakes were considered regardless of depth. Earthquakes in southwestern Japan were classified into three regions, i.e., 18 earthquakes west of 133E, 6 earthquakes east of 137E and 4 earthquakes in between. The data set consists of 316 horizontal components recorded at 54 stations: PHRI and KiK-net. KiK-net takes observations on the surface and in the ground, but in this paper, surface records were used.

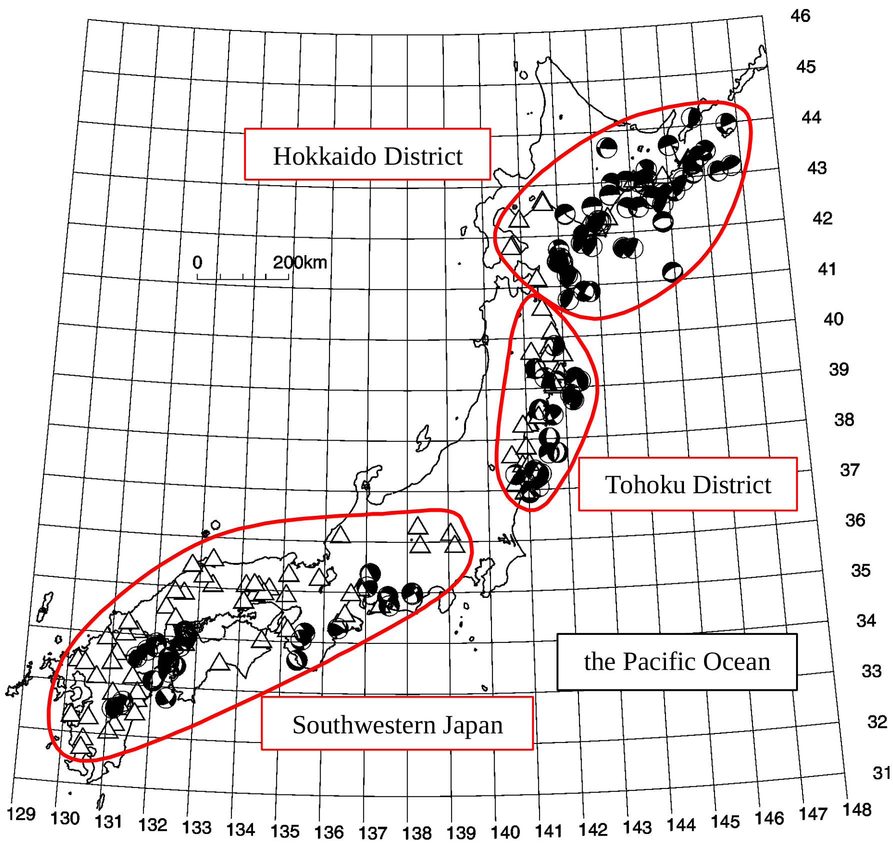


Figure 1 : Map of Japan, showing epicenter distribution of earthquakes analyzed in this study and observation stations.

METHOD

The source spectrum M(f) was evaluated from a displacement Fourier spectrum $U_0(f)$ of the observation records using the relation (1).

$$U_0(f) = H_g(f)\frac{R_{\theta\phi}M(f)}{4\pi\rho Vs^3 X}\exp(-\frac{\pi f X}{QsVs}) \tag{1}$$

Where, f = frequency, $R_{\theta\varphi}$ = radiation pattern, ρ = density, V_S = S wave velocity, X = hypocentral distance, Qs = quality factor of S wave and $H_g(f)$ = site characteristic.
ρ and V_S were taken as 3.2g/cm^3 and 4.5km/s for all regions (Takano [2], Fukuyama et al. [3]). $R_{\theta\varphi}$ was taken as 0.44 (Boore and Boatwright [4], Boore [5]). $H_g(f)$ was taken as 2.
An example of the acceleration waveform of an observation record is shown in Figure 2, and an acceleration Fourier spectrum is shown in Figure 3.
In this paper, the high frequency level M_{HF} of the source spectrum is defined as the level of amplitude fixed part in the high frequency region of the acceleration source spectrum. Two methods were used for assessment of M_{HF} according to the data conditions.
Method 1 is the case using a record of an observation station where the base rock is near the surface. In these observation stations, M_{HFg} is evaluated considering only $H_I(f)$=2. Further, let M_{HFs} calculated considering the difference in impedance by Equation (2), be the last value of M_{HF}.

$$M_{HFs} = M_{HFg}\sqrt{\frac{\rho_g Vs_g}{\rho_s Vs_s}} \tag{2}$$

Here, M_{HFs} and M_{HFg} show M_{HF} at the source position and the site, ρ_s and ρ_g show the density, and V_{Ss}, V_{Sg} show the S-wave velocity at the source location and the site. However, as the difference is thought to be small, ρ was ignored.
Method 2 is the case using a record of an observation station where its soil condition does not satisfy the aforesaid conditions. M_{HFg} (M_{HFg}') evaluated including site characteristics without modification, was divided by M_{HFg} evaluated from a station where Method 1 is applied to the same earthquake so as to give the site characteristic M_{HFg}'/M_{HFg}. By dividing M_{HFg}' of the earthquake to be assessed by the site characteristics, M_{HFg} of the reference observation station was evaluated. M_{HFs} was then evaluated using Equation (2) as in the case of Method 1, and this was taken as the final value of M_{HF}.
For earthquakes having records at observation stations where Method 1 can be applied, M_{HF} was evaluated by an identical technique, and other earthquakes were evaluated by Method 2. When plural M_{HF} are evaluated for one earthquake, their average values are calculated. Moreover, the stress parameter Δσ was evaluated by Equation (3) (Kato [6]), wherein, it is assumed that V_S=4.5km/s.

$$M_{HF} = (2.34Vs)^2\left(\frac{7}{16}\right)^{-2/3} M_0^{1/3}\Delta\sigma^{2/3} \tag{3}$$

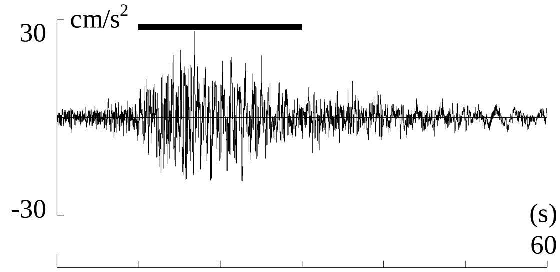


Figure 2 : Accelerogram of NS component recorded at Shiranuka during the earthquake of 15 Jan. 1993 (M_{JMA}7.5).

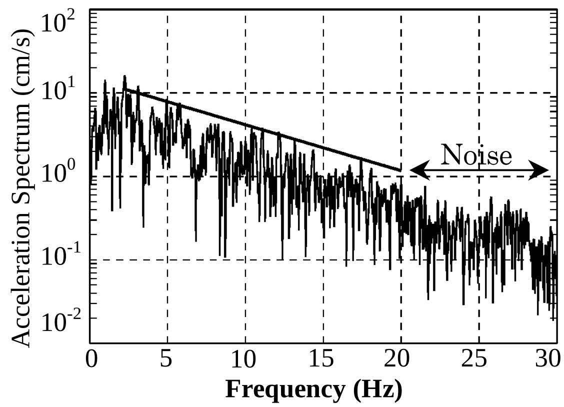


Figure 3 : Fourier amplitude spectrum of the NS component of ground acceleration recorded at Shiranuka during the earthquake of 15 Jan. 1993 (M_{JMA}7.5). Straight line was obtained by a least-squares fit to the data, and the level is adjusted to upper limit of the data.

PATH CHARACTERISTICS

The evaluation of Qs in Equation (1) will be described. It is assumed that the amplitude of an acceleration source spectrum at high frequency is fixed, and all the slopes of the high frequency region of the acceleration Fourier spectrum amplitude of observation records are based on the effect of Qs. Qs is evaluated from the slope of the acceleration Fourier spectrum amplitude of the observation records. The slope of the high frequency region calculated from the acceleration Fourier spectrum shown in Figure 3, is shown in this figure. It was assumed that Qs is not dependent on frequency.
The relation between Qs and hypocentral distance X in the Hokkaido district is shown in Figure 4(a). It is seen that Qs tends to become larger, the larger is X. Assuming there is a first-order correlation between the logarithm of Qs and the logarithm of X, Equation (4) was found:

$$\log Qs = 0.827 \log X + 1.106 \qquad (4)$$

Equation (4) is shown by the solid line in Figure 4. The relation between Qs and X which Mahdavian and Sasatani [7] evaluated for the Hokkaido district, is shown by the broken line in Figure 4(a). The result of the present study corresponds well with Mahdavian and Sasatani [7].

Qs, similarly evaluated for the Tohoku district and southwestern Japan, is shown in Figure 4(b), (c) respectively. As in the Hokkaido district, Qs in the Tohoku district and southwestern Japan also tends to depend on X. Regressions evaluated for the Tohoku district and southwestern Japan are respectively shown in equations (5) and (6), and by the solid line in Figure 4.

$$\log Qs = 0.581 \log X + 1.739 \tag{5}$$

$$\log Qs = 0.974 \log X + 0.568 \tag{6}$$

A superposition of regressions calculated for each region is shown in Figure 4(d). Qs for southwestern Japan is relatively small compared to other regions. In future studies, equations (4), (5) and (6) will be applied for all records.

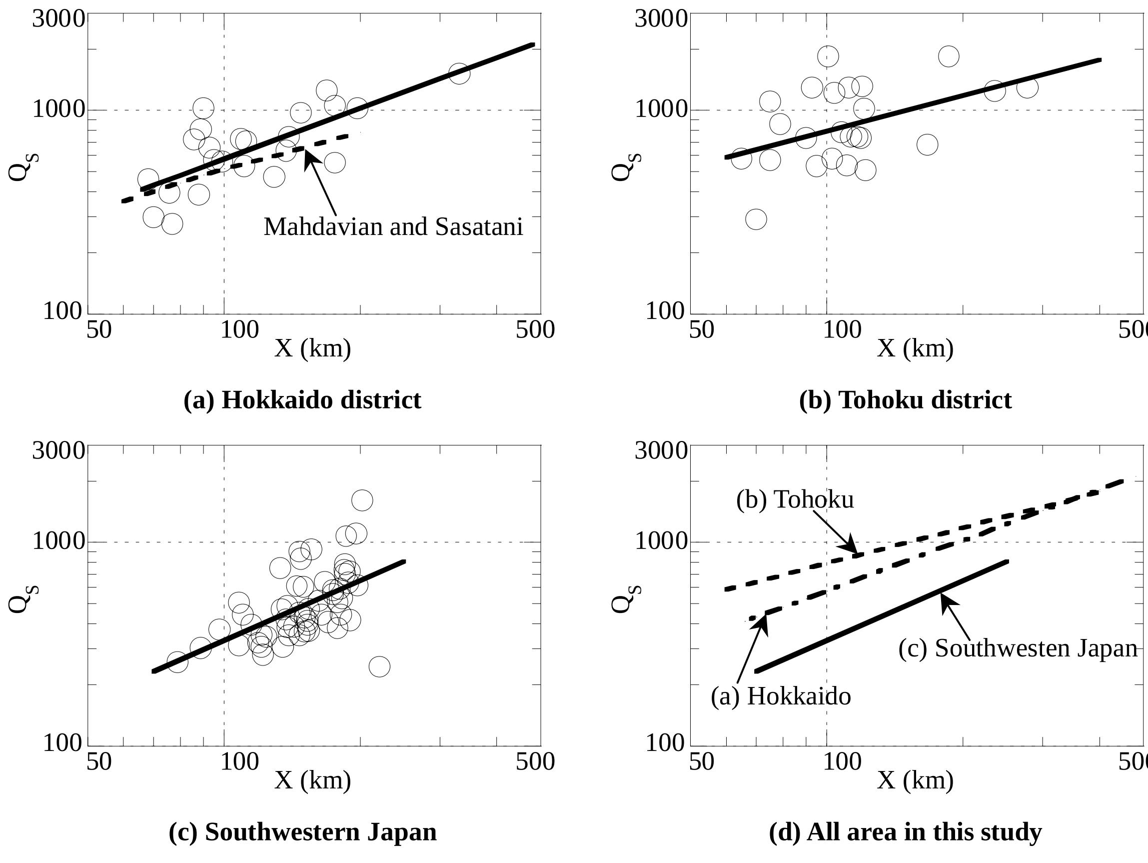


Figure 4 : Quality factor Qs versus hypocentral distance X analyzed in this study. Open circles represent the results of analysis in this study. Straight lines were obtained by a least-squares fit to the open-circle data.

SITE CHARACTERISTICS

As mentioned above, the assessment of M_{HF} uses two methods according to the conditions of the observation station. For method 2, it is necessary to evaluate the relative site characteristics for a reference observation station. The site characteristics are also independently evaluated for the Hokkaido district, the Tohoku district and southwestern Japan.

Hokkaido District

The reference station with site characteristics with little influence of soil amplification for direct evaluation of M_{HFg}, was taken as Shironuka of CRIEPI installed on base rock having V_S=1.5km/s. The source spectrum and M_{HFg} of the 1993 Kushiro-oki earthquake which was evaluated from observation records at Shironuka, is shown in Figure 5(a). As an example of an observation station for evaluating site characteristics, the source spectrum and M_{HFg}' of this earthquake evaluated from Kushiro of JMA is shown in Figure 5(b).

The site characteristics of observation stations evaluated in the Hokkaido district are shown in Figure 6(a). Station coefficient of the attenuation equation for peak ground acceleration by Molas and Yamazaki [8] is shown in Figure 6(a) by a solid triangle. The relative correlation between the average value of this study and the coefficient of Molas and Yamazaki [8] is the same.

Tohoku District

The reference station in the Tohoku district was taken as Namie of CRIEPI (V_{Sg}=0.61km/s). The evaluated site characteristic is shown in Figure 6(b), but this is converted to a level based on V_{Sg}=1.5km/s using Equation (2). In Figure 6(b), in addition to the station coefficient by Molas and Yamazaki [8], the site characteristic for V_{Sg}=1.5km/s evaluated based on site amplification factor according to Takemura et al. [9] is shown by a reverse solid triangle. From this figure, the site characteristic of this study corresponds with Molas and Yamazaki [8] and Takemura et al [9].

Southwestern Japan

In southwestern Japan, a large region is involved, and one station could not be taken as a reference station. M_{HFs} for V_{Ss}=4.5km/s evaluated by Method 1 was converted to M_{HFg} for V_{Sg}=1.5km/s, and this was taken as the amplitude level of the virtual reference observation station for V_{Sg}=1.5km/s. The site characteristics of southwestern Japan are shown in Figure 6(c).

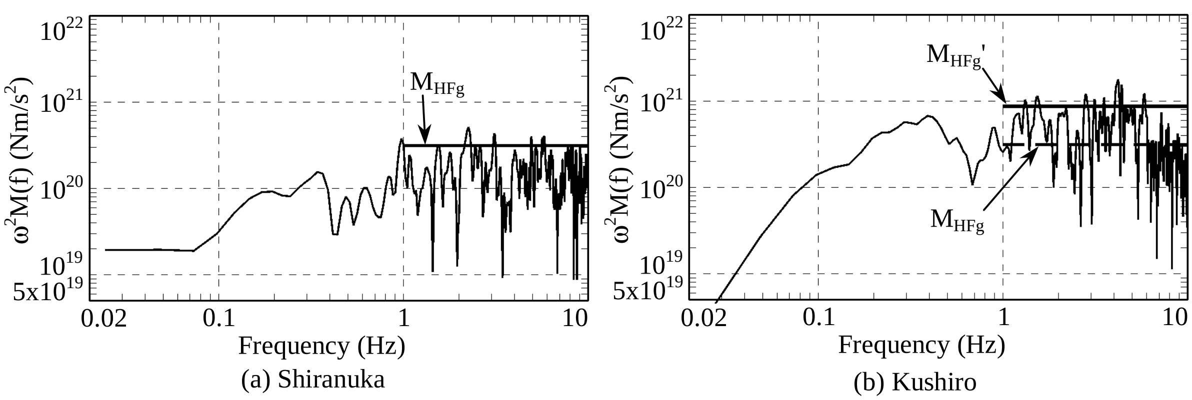


Figure 5 : Acceleration source spectra of the NS component at Shiranuka and Kushiro for the earthquake of 15 Jan. 1993 (M_{JMA}7.5). M_{HFg} is the constant level of the spectra higher than corner frequency at the rock site. M_{HFg}' is the level which envelops the spectra higher than corner frequency at the site except for rock site.

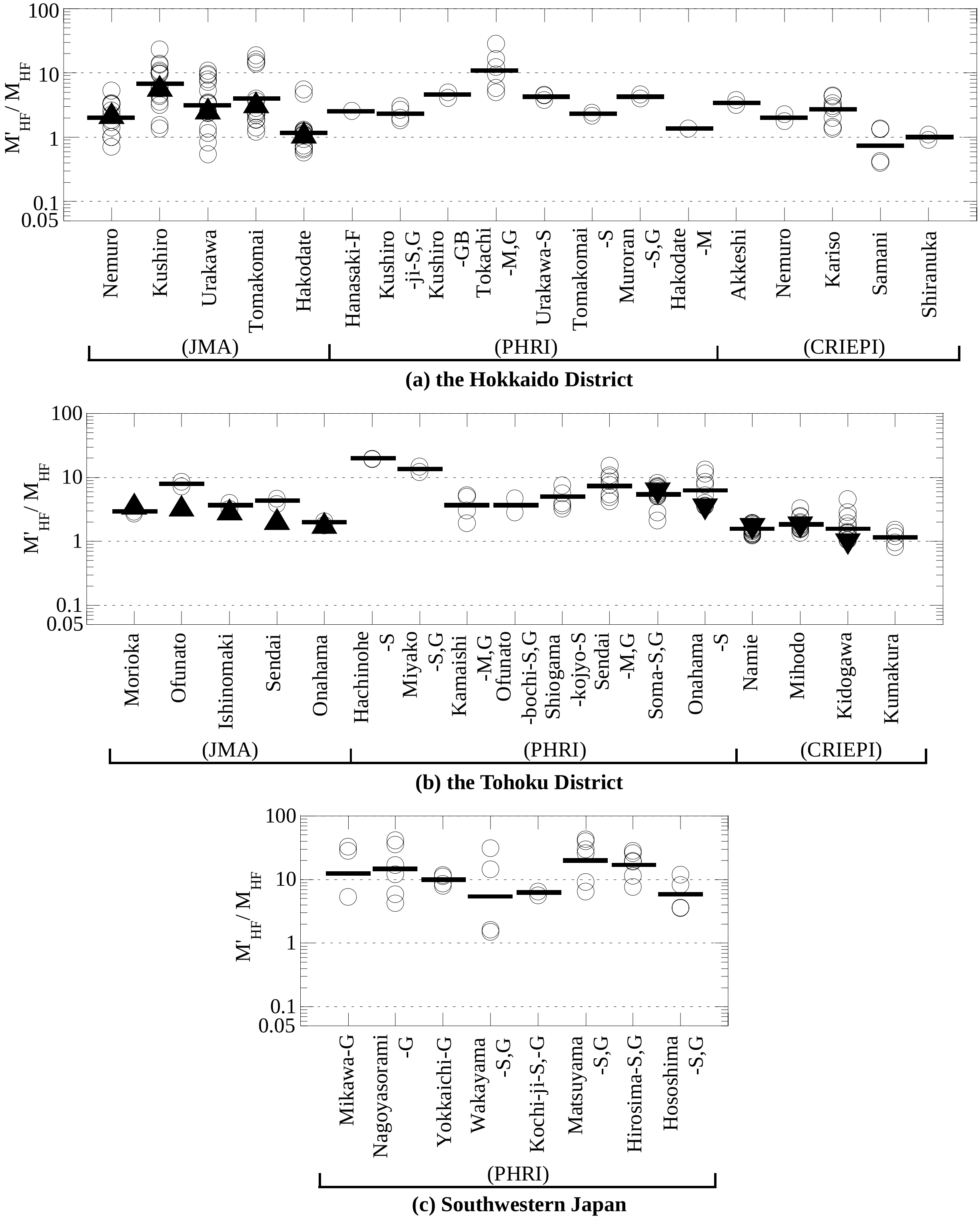


Figure 6 : Site characteristics of each site analyzed as M_{HF}'/ M_{HF} ratio in this study. Open circles apply to the ratio of each record in this study; horizontal bars apply to average of those data. Solid triangles apply to the data from Molas and Yamazaki (1995); solid reverse triangles apply to the data from Takemura et al. (1991).

M_{HF} AND STRESS PARAMETER

Hokkaido District

The relation between M_{HF} for the Hokkaido district and the seismic moment M_0 according to Harvard University, is shown in Figure 7(a). The sloping lines in the figure show the stress parameter $\Delta\sigma$ =5, 10, 20, 40, 80MPa based on equation (3). The relation between $\Delta\sigma$ and focal depth is shown in Figure 7(b). $\Delta\sigma$ of the Sub-type is approx. 1-80MPa, and the average value is 7.7MPa.

$\Delta\sigma$ of the DE-type is approx. 20-80MPa, and the average value 29.7MPa, is clearly larger than the Sub-type. From Fig. 7(a), $\Delta\sigma$ of an intra-slab earthquake has a different slope according to M_0. $\Delta\sigma$ of a medium and small earthquake having M_0<1E+19Nm is approx. 5-70MPa, and the average value is 25.0MPa. On the other hand, $\Delta\sigma$ of a major earthquake of M_0>1E+19Nm is approx. 60 to 80MPa, and the average value is 70.1MPa. $\Delta\sigma$ of a major earthquake is the upper limit of medium and small earthquakes.

Tohoku District

The relation between M_{HF} and M_0 for the Tohoku district is shown in Figure 8(a), and the relation between $\Delta\sigma$ and focal depth is shown in Figure 8(b). $\Delta\sigma$ of the DE-type is approx. 7-51MPa, and the average value is 26.3MPa. $\Delta\sigma$ of the DC-type is approx. 8-69MPa, and the average value is 22.1MPa. Therefore, $\Delta\sigma$ of the DE-type and DC-type are approximately identical.

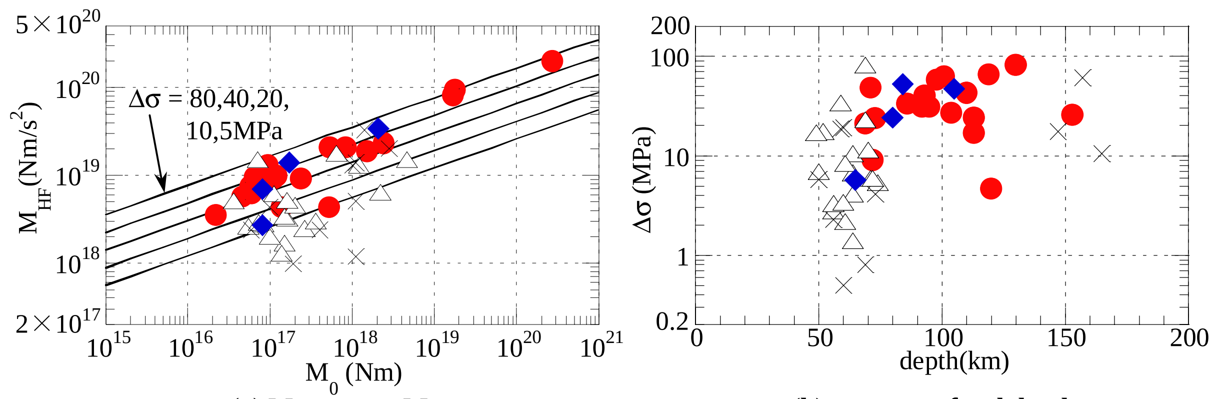
The relation between M_{HF} and M_0 for all earthquakes in the Hokkaido district and the Tohoku district is shown in Figure 9(a). $\Delta\sigma$ for intra-slab earthquakes in the Hokkaido district and the Tohoku district is almost the same. M_0>1E+19Nm is taken as a large group, M_0<5E+17Nm is taken as a small group, and those in between are taken as a medium-group. $\Delta\sigma$ for the small group varies greatly with the earthquake. However, $\Delta\sigma$ of the large group is fixed and is distributed near the upper limit of the small group.

The relation between $\Delta\sigma$ and focal depth for intra-slab earthquakes in the Tohoku district is classified according to earthquake magnitude, and is shown in Figure 9(b). $\Delta\sigma$ increases as the depth of the small group increases. However, $\Delta\sigma$ for the medium group and large group is constant regardless of depth.

Southwestern Japan

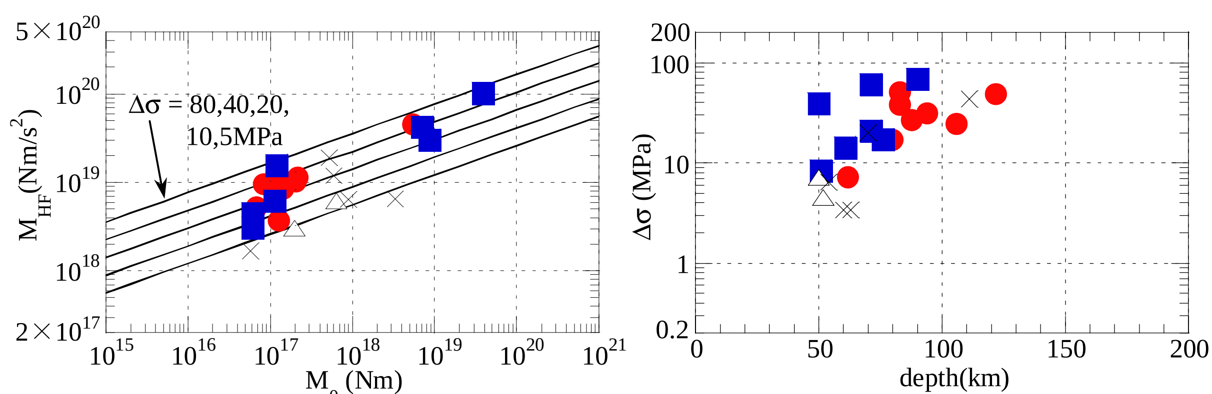
The relation between M_{HF} and M_0 of southwestern Japan is shown in Figure 10(a). The relation between $\Delta\sigma$ and focal depth is shown in Figure 10(b). $\Delta\sigma$ of the eastern part, central part and western part are comparable. As in the Hokkaido district and the Tohoku districts, $\Delta\sigma$ of intra-slab earthquakes in southwestern Japan differ according to M_0. $\Delta\sigma$ of an earthquake having M_0>5E+17Nm is larger than for an earthquake having M_0<5E+17Nm. However, the difference in $\Delta\sigma$ of the medium group and large group seen in earthquakes in the Hokkaido district and the Tohoku district, is not observed.

The relation between M_{HF} and M_0 for intra-slab earthquakes in southwestern Japan, the Hokkaido district and the Tohoku district is shown in Figure 11(a). Southwestern Japan is shown as the Philippine Sea plate, while the Hokkaido district and the Tohoku district are shown as the Pacific plate. As in Figure 9(a), a classification into three groups is made according to M_0, and the relation between $\Delta\sigma$ and focal depth is shown in (b)-(d) for each group. $\Delta\sigma$ of the small group largely varies with the earthquake, and its upper limit is approx. 70MPa. $\Delta\sigma$ of the medium group shows no difference due to the plate and focal depth, and is constant in the range of approx. 20-70MPa. In the large group, it varies with the plate, and although for four earthquakes in the Pacific plate it is constant at approx. 60-80MPa, the values for two earthquakes in the Philippine Sea plate are 10 and 40MPa, i.e., different.



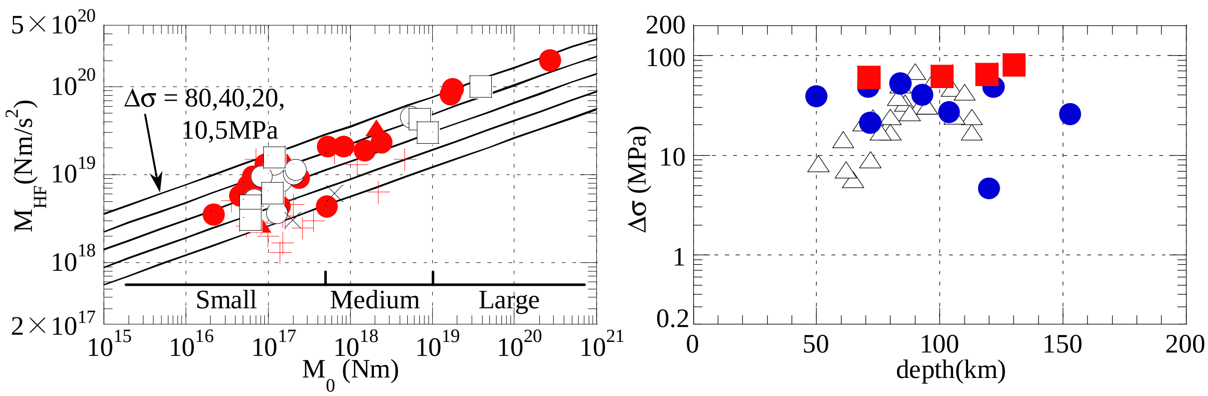
(a) M_{HF} versus M_0 **(b) $\Delta\sigma$ versus focal depth**

Figure 7 : M_{HF}, seismic moment M_0, stress parameter $\Delta\sigma$ and focal depth for the Hokkaido district. Solid circles represent DE-type; solid lozenges represent Hin-type; open triangles represent Sub-type; X's represent other type. Solid line shows the relation of equation (3) for each stress parameter $\Delta\sigma$.



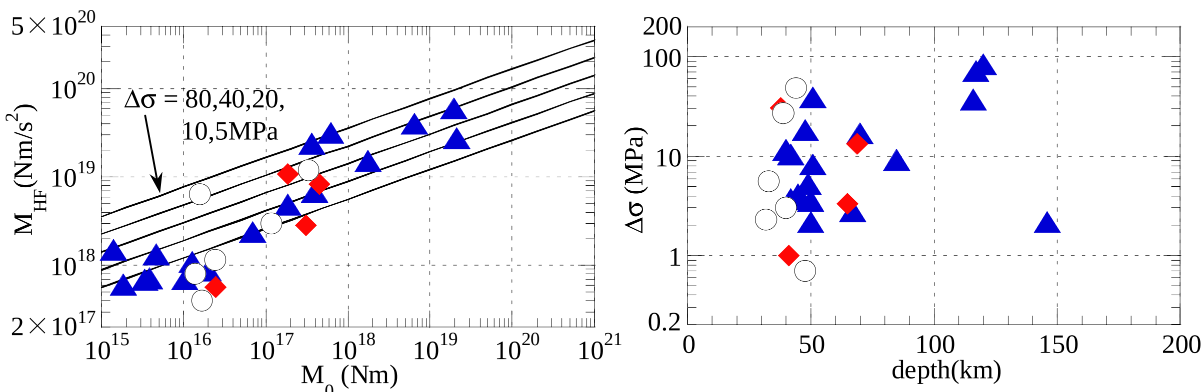
(a) M_{HF} versus M_0 **(b) $\Delta\sigma$ versus focal depth**

Figure 8 : M_{HF}, seismic moment M_0, stress parameter $\Delta\sigma$ and focal depth for the Tohoku district. Solid circles represent DE-type; solid squares represent DC-type; open triangles represent Sub-type; X's represent other type. Solid line shows the relation of equation (3) for each stress parameter $\Delta\sigma$.



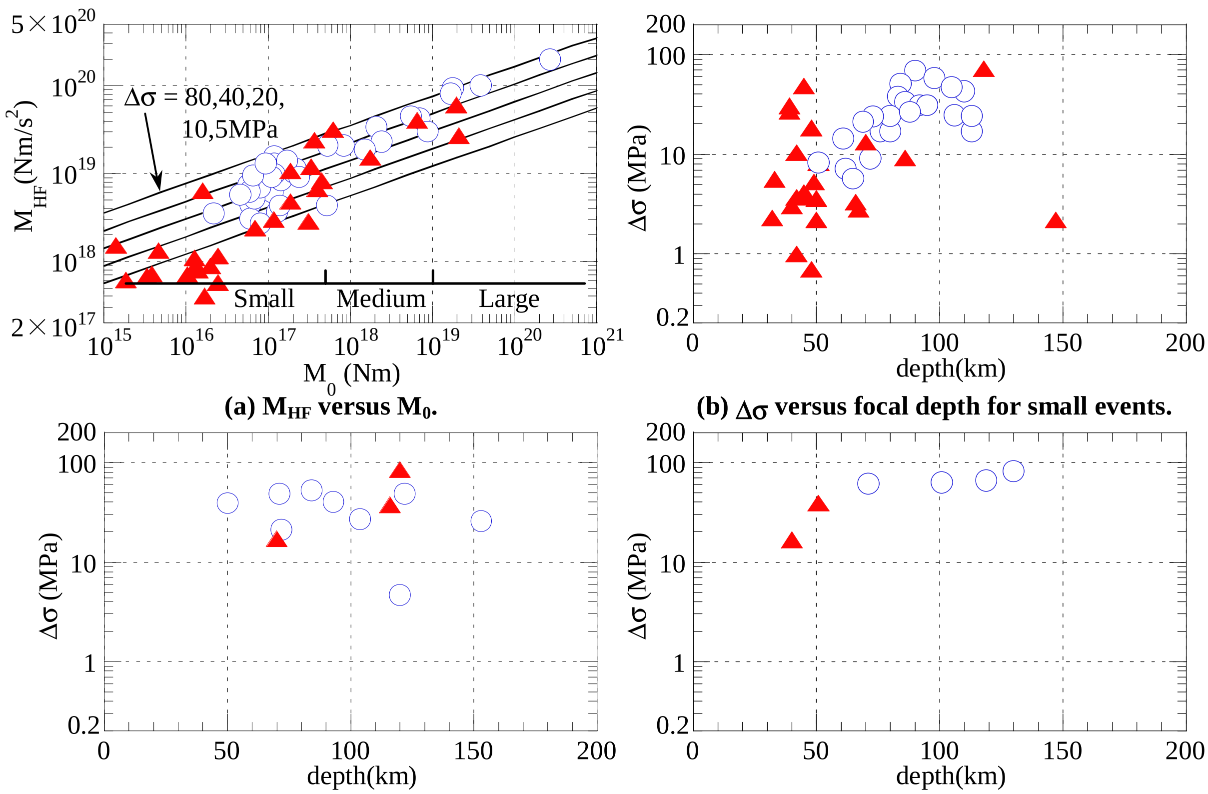
(a) M_{HF} versus M_0. **(b) $\Delta\sigma$ versus focal depth.**

Figure 9 : M_{HF}, seismic moment M_0, stress parameter $\Delta\sigma$ and focal depth for Hokkaido and Tohoku district. (a) Solid circles, solid triangles and crosses represent respectively DE, Hin and Sub-type for the Hokkaido district; open circles, open squares and X's represent respectively DE, DC and Sub-type for the Tohoku district. Solid line shows the relation of equation (3) for each stress parameter $\Delta\sigma$. (b) Solid squares, solid circles and open triangles represent respectively large, medium and small events indicated in (a).



(a) M_{HF} versus M_0 **(b) $\Delta\sigma$ versus focal depth**

Figure 10 : M_{HF}, seismic moment M_0, stress parameter $\Delta\sigma$ and focal depth for southwestern Japan. Open circles represent the western part; solid lozenges represent the central part; solid triangles represent eastern part. Solid line shows the relation of equation (3) for each stress parameter $\Delta\sigma$.



(a) M_{HF} versus M_0.

(b) Δσ versus focal depth for small events.

(c) Δσ versus focal depth for medium events.

(d) Δσ versus focal depth for large events.

Figure 11 : M_{HF}, seismic moment M_0, stress parameter Δσ and focal depth for earthquakes in Japan. Open circles represent the intraslab earthquakes in the Pacific plate; Solid triangles represent the intraslab earthquakes in the Philippine Sea plate.

CONCLUSION

The acceleration source spectra were evaluated by eliminating the effects of propagation path and site characteristics from observation records. The target events are intermediate depth earthquakes in the Hokkaido district and the Tohoku district, and intra-slab earthquakes of southwestern Japan. A stress parameter Δσ was evaluated from the high frequency level M_{HF} defined as the level of amplitude fixed part in the high frequency region of the acceleration source spectrum, and the relation between Δσ, regionality, focal mechanism, earthquake magnitude and focal depth was examined. The results are described below.

1. The Q value evaluated for the Hokkaido district, the Tohoku district and southwestern Japan showed a tendency to increase depending on the hypocentral distance. Moreover, the Q value of the Hokkaido district and the Tohoku district is large compared with southwestern Japan.
2. Δσ of the Sub-type of the Hokkaido district is approx. 1-80MPa. Δσ of the DE-type is about 20-80MPa. Δσ of the DE-type is clearly larger than that of the Sub-type.
3. Δσ of intra-slab earthquakes of the Hokkaido district and the Tohoku district are identical, and vary with earthquake magnitude. Δσ of the small group varies greatly with the earthquake, whereas Δσ of the large group is constant and identical to the upper limit of the small group. Moreover, for the small group, Δσ tends to vary largely, whereas Δσ of the medium group and large group are constant regardless of depth.

4. $\Delta\sigma$ of intra-slab earthquakes of southwestern Japan does not depend on the region. $\Delta\sigma$ of intra-slab earthquakes in southwestern Japan are larger for the medium group and large group than for the small group.

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