Real-time Prediction of Earthquake Ground Motion Using Seismic Records Observed in Deep Boreholes

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In the case of local earthquakes, a method for predicting earthquake ground motion directly using P-waves observed in deep boreholes, makes it possible to issue earthquake early warnings more simply and reliably compared with the present system. In addition, a method for predicting earthquake ground motion using S-waves observed in deep boreholes and S-wave velocity structures, makes it possible to show the planar distribution of earthquake ground motion, which may narrow down the areas where emergency inspections should be conducted following earthquakes. To develop those two methods, investigations were conducted into the relationship between the peak amplitudes of earthquake motion on the surface and those in deep boreholes using seismic records from KiK-net.

**Keywords:** earthquake early warning (EEW), deep borehole, peak amplitude, KiK-net, S-wave velocity structure, radiation pattern, propagation path, site amplification

1. Introduction

In Japan in 1992 an earthquake early warning (EEW) system using P-waves on the surface was installed, to ensure train operating safety in areas subjected to strong seismic motion during earthquakes [1]. The present EEW system predicts earthquake ground motion on the basis of estimated earthquake information such as the epicentral distance and the magnitude, using initial P-waves observed on the surface [2]. In the case of local earthquakes occurring beneath the Tokyo Metropolitan Area, a method for predicting earthquake ground motion using S-waves observed in deep boreholes, will make it possible to issue EEWs more simply and reliably compared with the present system.

Train operations are also stopped following earthquakes in areas where there is suspected damage to railway structures caused by strong seismic motion. Train operation control areas are defined on the basis of the data recorded by trackside seismographs installed at intervals of 5 to 40 km. The emergency inspection of railway structures is performed in the areas where train operations have stopped; inspections are therefore time consuming due to long distances between seismographs. A method for predicting S-waves on the surface using S-waves observed in deep boreholes and S-wave velocity structures, will make it possible to show the planar distribution of earthquake ground motion in train operation control areas in the aftermath of earthquakes. This information may narrow down the areas where emergency inspections should be conducted.

For the abovementioned two purposes, investigations were carried out into the relationship between the peak amplitudes of earthquake motion on the surface and those in deep boreholes, using the seismic records from KiK-net stations in the Kanto Basin.

2. Data used in this study

This study used earthquake accelerograms observed at the 12 seismic stations belonging to the KiK-net whose borehole depths were deeper than the top face of the Pre-Neogene basement beneath the Kanto Basin [3]. Figure 1 shows the location of the seismic stations of KiK-net in and around the Kanto Basin, which includes those 12 seismic stations. Table 1 shows the details of seismic stations used in this study.

Figure 2 shows the distribution of epicenters and the focal depths of earthquakes used in this study. 215 local earthquakes whose epicenters were located in and around the Kanto Region were selected. Their JMA (Japan Meteorological Agency) magnitudes ranged from 4.5 to 7.0 and with most of the dataset between 4.5 to 5.5. Figure 3 is the histogram of peak ground accelerations observed in all the stations for earthquakes shown in Fig. 2. Since the dataset for peak ground accelerations mainly comprises values reaching tens of cm/s², the effects of the soil non-linearity which appears during strong seismic motion are considered to be very small in this dataset.

![Fig. 1 Location of seismic stations of KiK-net in and around the Kanto Basin](image)

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**Keywords:** earthquake early warning (EEW), deep borehole, peak amplitude, KiK-net, S-wave velocity structure, radiation pattern, propagation path, site amplification
The onset of P-waves and S-waves was manually picked using vertical and horizontal components, respectively. Data which showed unclear arrival of P-waves and S-waves were excluded. The peak amplitudes of P-waves and S-waves were obtained using vertical components and the vector sums of horizontal components, respectively. Accelerations and velocities were processed by integrating accelerations through the band-pass filter, using third-order Butterworth type with the cutoff frequencies of 0.1 and 20 Hz. Figure 4 shows examples of acceleration and velocity waveforms.

### Table 1 Details of seismic stations used in this study

| Code   | Name        | Latitude (° N) | Longitude (° E) | Station height (m) | Depth of borehole (m) | Number of seismic data |
|--------|-------------|----------------|-----------------|--------------------|-----------------------|------------------------|
| CHBH04 | SHIMOHSA    | 35.7966        | 140.0206        | 23                 | 2300                  | 138                    |
| CHBH13 | NARITA      | 35.8307        | 140.2980        | 12                 | 1300                  | 154                    |
| CHBH14 | CHOUSHI-C   | 35.7342        | 140.8230        | 2                  | 525                   | 78                     |
| CHBH19 | HASUNUMA    | 35.5943        | 140.5107        | 1                  | 1630                  | 76                     |
| GNMH06 | TATEBAYASHI | 36.2441        | 139.5443        | 20                 | 1203                  | 36                     |
| IBRH07 | EDOSAKI     | 35.9521        | 140.3301        | 3                  | 1200                  | 156                    |
| IBRH10 | ISHIGE      | 36.1112        | 139.9889        | 15                 | 900                   | 139                    |
| IBRH17 | KASUMIGAURA | 36.0864        | 140.3140        | 20                 | 510                   | 167                    |
| IBRH21 | TSUKUBA-S   | 35.9814        | 140.1050        | 22                 | 929                   | 71                     |
| SITH01 | IWATSUKI    | 35.6539        | 139.4704        | 45                 | 3510                  | 76                     |
| TKYH02 | FUCHU       | 35.9290        | 139.7349        | 8                  | 3000                  | 70                     |
| TKYH11 | KOTO        | 35.6114        | 139.8125        | 6                  | 3000                  | 70                     |

Fig. 2 Distribution of epicenters and focal depths of earthquakes used in this study

Fig. 3 Histogram of peak ground accelerations observed in all the stations

The onset of P-waves and S-waves was manually picked using vertical and horizontal components, respectively. Data which showed unclear arrival of P-waves and S-waves were excluded. The peak amplitudes of P-waves and S-waves were obtained using vertical components and the vector sums of horizontal components, respectively. Accelerations and velocities were processed by integrating accelerations through the band-pass filter, using third-order Butterworth type with the cutoff frequencies of 0.1 and 20 Hz. Figure 4 shows examples of acceleration and velocity waveforms.

#### 3. Lead time until the arrival of S-waves using P-waves observed in deep boreholes

To evaluate the lead time by the method using P-waves in deep boreholes, the time differences between the arrivals of S-waves on the surface and those of P-waves in deep boreholes were calculated. Figure 5 shows the relationship between these time differences and hypocentral distances. In the case of short hypocentral distances of tens of km, a lead time of several seconds is expected. Figure 6 shows the time difference between the arrivals of S-waves and those of P-waves on the surface. The average time differences are about 0.5 s longer when the method using P-waves in deep boreholes was used than when P-waves on the surface were referred to.

To evaluate the lead time for each station, Fig. 7 shows the average time differences between the arrivals of P-waves observed on the surface and those in deep boreholes against borehole depths. The average time differences ranged from 0.1 to 1.2 and were related to borehole depth. In station SITH01 with a borehole depth of 3510 meters, the lead time was expected to be about 1.2 s; this would make it possible to issue warnings slightly earlier using P-waves observed in deep boreholes than those on the surface.

Figure 8 shows the probability distribution and the cumulative probability distribution of the time from the arrival of P-waves to the peak acceleration of P-waves in deep boreholes. The peak accelerations appear within 3 s after the arrival of P-waves in about 80% of the data whose hypocentral distances are less than 80 km, as shown in Fig. 8 (a). On the other hand, peak accelerations appear within 3s
will be possible to rapidly obtain the peak acceleration of P-waves if hypocentral distances are greater than 80 km, as shown in Fig. 8; this shows that with near-field earthquakes, it will be possible to rapidly obtain the peak acceleration of P-waves in deep boreholes.

### 4. Relationship between amplitudes in deep boreholes and those on the surface

#### 4.1 Relationship between amplitudes of P-waves and S-waves in deep boreholes

When a seismic source is a double-couple point source, P-wave and S-wave spectra observed in the far-field $O(\omega)$ are expressed as

$$O_P^S(\omega) = \frac{R_{0b}}{4\pi\rho\nu_P} \tilde{M}(\omega) \frac{1}{r} \exp\left(-\frac{\omega}{2Q_P \nu_P} r \right), \quad (1)$$

$$O_S^S(\omega) = \frac{R_{0b}}{4\pi\rho\nu_S} \tilde{M}(\omega) \frac{1}{r} \exp\left(-\frac{\omega}{2\nu_S \nu_S} r \right), \quad (2)$$

where $\rho$ and $\nu$ are density and wave-velocity near the source field, $R_{0b}$ is radiation coefficient, $\tilde{M}(\omega)$ shows seismic moment acting on the source point, $r$ shows hypocentral distance, $\omega$ is circular frequency, $Q$ is quality factor in the propagation path. The subscript $b$ stands for borehole. The subscript or superscript $P$ and $S$ stand for P-wave and
Fig. 7  Average time differences between the arrival of P-waves observed on the surface and those in deep boreholes against borehole depths

Fig. 8  Probability distributions and cumulative probability distributions of the time from the arrival of P-waves to the peak acceleration of P-waves in deep boreholes

S-wave, respectively. By taking the common logarithm between (1) and (2), it is possible to derive the relationship between the amplitude of a P-wave and that of an S-wave in deep boreholes as

$$\log O_i^S(\omega) = \log O_i^P(\omega) + a_i(\omega),$$  \hspace{1cm} (3)

where $a_i$ is the parameter expressed as

$$a_i(\omega) = \log \frac{V_{P_i}^2}{V_{S_i}^2} + \log R_{b\omega}^S + \log \cosh \left( \frac{r_{00}}{2 \cdot Q_{Sb}^\omega} \cdot \frac{1}{Q_{Pb}^\omega} \right).$$  \hspace{1cm} (4)

Estimations were made of parameters $a_i$, representing P/S wave velocity ratios around the source regions, radiation coefficients, and attenuations of the propagation paths, using the peak amplitudes of P-waves and S-waves observed in deep boreholes, by minimizing the residuals between the calculations using (3) and the observations shown in Fig. 9. The superscripts $A$ and $V$ stand for the parameters estimated from peak accelerations and peak velocities, respectively.

4.2 Relationship between the amplitudes of S-waves in deep boreholes and those on the surface

By using the transfer function $G(\omega)$ between the basement and the surface, the relationship between the S-waves in deep boreholes and those on the surface is expressed as

$$O_i(\omega) = \log O_i^b(\omega) - G(\omega).$$  \hspace{1cm} (5)

The subscript $s$ stands for surface. The common logarithm is taken from either side of (5), thus

$$\log O_i(\omega) = \log O_i^b(\omega) + a_i(\omega),$$  \hspace{1cm} (6)

where $a_i$ is the parameter expressed as

$$a_i(\omega) = \log G(\omega).$$  \hspace{1cm} (7)

Equations (5) ~ (7) are valid for P-wave and S-wave. However, this study only looks at S-wave. Estimations were made of parameters $a_i$ which represent site amplification factors at seismic stations, using the peak amplitudes of S-waves observed in deep boreholes and those on the surface, by minimizing the residuals between calculations using (6) and observations shown in Fig. 10.

4.3 Relationship between the amplitude of P-waves in deep boreholes and the S-waves on the surface

Through equations (3) and (6), the relationship between the P-waves in deep boreholes and the S-waves on the surface is then

$$\log O_i^P(\omega) = \log O_i^S(\omega) + b(\omega),$$  \hspace{1cm} (8)

where $b$ is the parameter expressed as

$$b(\omega) = a_i(\omega) + a_i(\omega).$$  \hspace{1cm} (9)

Estimations were made of parameters $b$, using the peak amplitudes of P-waves in deep boreholes and the S-waves observed on the surface, by minimizing the residuals between calculations using equation (8) and observations shown in Fig. 11.
Fig. 9 An example of the relationship of the peak accelerations and the peak velocities between $O_s$ and $O_b$ (CHBH04)

Fig. 10 An example of the relationship of the peak accelerations and peak velocities between $O_s$ and $O_b$ (CHBH04)

Fig. 11 An example of the relationship of the peak accelerations and velocities between $O_s$ and $O_b$ (CHBH04)
5. Discussion

Figure 12 shows the parameters $a_1$ and $a_2$ for each seismic station. $a_1$ are smaller than $a_2$ except IBRH21 mainly because attenuations of in the propagation paths are large especially in the high frequency range. On the other hand, $a_2$ are different from $a_1$ for each station due to the variation of the frequency contents of earthquake ground motions amplified by S-wave velocity structures at seismic stations. $a_2$ are larger than $a_1$ in most of the seismic stations; therefore, S-wave velocity structures at seismic stations has a greater influence on the relationship between the S-waves on the surface and the P-waves in deep boreholes than with P/S wave velocity ratios around source regions, radiation coefficients, and attenuations of propagation paths.

Figure 13 shows the correlation coefficients between the peak amplitudes for each station. The correlation coefficients between calculations using equation (3) and observations range from 0.7 to 0.9. On the other hand, the correlation coefficients between calculations using equation (6) and observations have higher values in the range from 0.8 to 0.9. The correlation coefficients between calculations using equation (8) and observations range from 0.7 to 0.9 and are similar results using equation (3). Results suggest that the variability of radiation patterns and propagation paths from individual earthquakes influence somewhat the accuracy of earthquake ground motion predictions when using P-waves observed in deep boreholes. The correlation coefficient averaged over all the stations is about 0.8; therefore, predicted earthquake ground motion is sufficiently accurate to issue EEWs, using P-waves observed in deep boreholes. In addition, the peak amplitudes of S-waves in deep boreholes and site amplification factors on the basis of S-wave velocity structures provide very precise prediction of earthquake ground motion. Results suggest that it will be possible to predict earthquake ground motion following earthquakes even in locations where no seismic station is installed on the surface if S-wave velocity structures at these sites have previously been evaluated to a high degree of accuracy.

6. Conclusions

To develop a method for predicting earthquake ground motion using seismic records observed in deep boreholes for EEWs and gather the necessary data to narrow down the areas where emergency inspections should be conducted following earthquakes, investigations were carried out into the relationship between the peak amplitudes of earthquake motions on the surface and those in deep boreholes, using the seismic records of KiK-net stations in the Kanto Basin. The following results were obtained:

1) The lead time by the method under which P-waves observed in deep boreholes are used was evaluated as being from 0.1 to 1.2 s in all the stations used in this study. Also, it was confirmed that the peak accelerations of P-waves in deep boreholes tended to be obtained rapidly in the case of short hypocentral distances. Therefore, in the case of local earthquakes, slightly earlier warnings can be expected when using P-waves observed in deep boreholes, compared with the present warning system.

2) For the prediction of the peak amplitude of S-waves on the surface using the peak amplitude of P-waves in deep boreholes, parameters representing P/S wave velocity ratios around source regions, radiation coefficients, and attenuations of propagation paths, using the relationship between peak amplitude of P-waves and S-waves observed in deep boreholes were obtained. The correlation coefficients of these relationships were slightly lower than those for the site amplification factors due to the variability of the radiation patterns and the propagation paths of individual earthquakes. It will however be possible to rapidly predict earthquake ground motion with sufficient accuracy to issue EEWs, using the peak amplitude of P-waves in deep boreholes.

3) For the prediction of peak amplitude of S-waves using the peak amplitude of S-waves in deep boreholes, parameters representing site amplification factors at seismic stations, using the relationship between the peak amplitude of S-waves observed in deep boreholes and those on the surface were obtained. The correlation coefficients of these relationships have high values for most of the seismic stations. When the peak amplitude of S-waves in deep boreholes and the site amplification factors on the basis of S-wave velocity structures are known, it is possible to predict earthquake ground motion to a high degree of accuracy.
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References

[1] Nakamura, Y., “Research and development of intelligent earthquake disaster prevention systems UrEDAS and HERAS,” Journal of Structural Mechanics and Earthquake Engineering, No.531/ I-34, pp.1-33, January 1996 (in Japanese).

[2] Ashiya, K., Tsukada, S., Taya, S., Odaka, T., Sato, S., Ohtake, K., and Nakamura, H., “Earthquake quick alarm system using nowcast earthquake information,” RTRI Report, Vol.17, No.8, pp.1-6, August 2003 (in Japanese).

[3] Hayashi, H., Kasahara, K., and Kimura, H., “Pre-Neogene basement rocks beneath the Kanto Plain, central Japan,” The Journal of the Geological Society of Japan, Vol.112, No.1, pp.2-13, January 2006 (in Japanese).

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