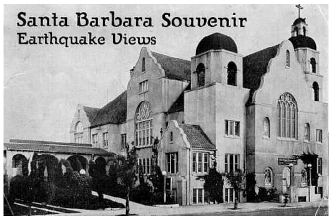

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SITE-RESPONSE ESTIMATION BY 1D HETEROGENEOUS VELOCITY MODEL USING BOREHOLE LOG AND ITS RELATIONSHIP TO DAMPING FACTOR

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ABSTRACT

The site response transfer functions using 1D layered velocity models based on microtremor array exploration in the Niigata area, Japan, were examined whether it would be possible to explain the estimated high-frequency site responses using observed earthquake records or not. Our results showed the site response transfer functions were relatively larger in the frequency over about 3 or 6 Hz than the estimated site responses. Therefore, to improve a 1D velocity model's applicability in estimating high-frequency site responses, we proposed to modify an existing 1D layered velocity model by taking into account a random fluctuation of velocity, so-called 1D heterogeneous velocity model. Consequently, the site response transfer functions using 1D heterogeneous velocity models could well explain the high-frequency-decay of the estimated site responses. Moreover, we demonstrate that the high-frequency decay of the estimated site responses can be also explained by the site responses from transfer functions using the 1D layered velocity models with additional damping factor. Our results also suggest that the high-frequency decay of site responses in this area is caused by attenuation from random velocity fluctuation of sedimentary layers due to heterogeneity.

INTRODUCTION

The Niigata area, central Japan, is often hit by severely damaged earthquakes, such as the 1964 Niigata earthquake (M_{JMA}7.5), the 2004 Niigataken Chuetsu earthquake (M_{JMA}6.8) and the 2007 Niigataken Chuetsu-oki earthquake(M_{JMA}6.8). For example, during the old 1964 Niigata earthquake, the sloshing of liquid of large oil storage tank was excited by the long-period ground motion induced from Niigata sedimentary layers. Consequently, the sloshing caused a tank fire that burned down about 350 nearby houses [CRIEPI (1964)]. Therefore, relevant geophysical surveys for estimating deep S wave velocity structure that aim to simulate long-period ground motion, such as microtremor array exploration, have been eagerly conducted in this area [e.g. Sato et al. (2009)]. Meanwhile, during the recent 2007 Niigataken Chuetsu-oki earthquake, strong ground motions were recorded at Nuclear Power Station located in Niigata prefecture, whose PGA is larger than the design level. This means that the estimation of high-frequency site response is also important to reduce earthquake disaster around this area. However, as described above, since the velocity models in this area were mainly constructed for the purpose of the long-period ground motion simulation, it is essential to investigate the applicability of these models to estimate high-frequency site responses.

In this study, we therefore first examined whether the site response transfer functions using 1D layered velocity models based on microtremor array exploration would be possible to explain the estimated high-frequency site responses, which were derived from the separation of source, path and site effect by nonlinear inversion of observed S wave data [e.g. Iwata and Irikura(1986)]. And then we clarified how to modify the 1D layered velocity models based on microtemor array exploration for the better explanation of high-frequency site responses in this area. The estimated site responses from inversion by using observed data show the different decay characteristics for high-frequency over about 5 Hz at the different sites, whose characteristics cannot be explained by transfer functions using 1D layered velocity models based on microtremor array exploration. From our investigation using the borehole-log in the Niigata area, we found that the velocity structure was strongly characterized by random fluctuations reflecting heterogeneous media, which was not considered by our 1D layered velocity models. We therefore show that the site response transfer functions using 1D heterogeneous velocity models, which were superposed a random fluctuation on 1D layered velocity models, can well explain the high-frequency decay of the estimated site responses. Moreover, we demonstrate that the high-frequency decay of the estimated site responses can be also explained by the site responses from transfer functions using the 1D layered velocity models with additional damping factor. Our results also suggest that the high-frequency decay of site responses in this area is caused by attenuation from random velocity fluctuation of sedimentary layers due to heterogeneity.

COMPARISON OF SITE RESPONSES

Site responses from observed data

We used strong motion records from 48 stations located in the Niigagta area. 28 stations are K-NET (Kinoshita [1998]), 19 stations are KiK-net (e.g. Aoi et al. [2000]), and one station (KSH) is the Kashiwazaki-Kariwa NPS of TEPCO. In total, we analyzed 668 horizontal surface records from 13 earthquakes with magnitude from 3.7 to 5.0 and hypocentral distances less than 100 km (see Fig. 1(a)). We used an S wave time window of 5-sec starting approximately 1-sec before S wave arrival, which applied a cosine taper to both ends of data for a width of 20% of the time window. The observed spectra used in inversion were calculated by vector summation of two horizontal components of observed spectra, and were smoothed by using a variable frequency band of 20 % at each 161 predefined frequencies between 0.5 and 20 Hz.

The separation of source, path and site effect by nonlinear inversion of observed S wave data used in this study was originally developed by Iwata and Irikura (1986). This inversion requires a constraint to avoid trade-off between three effects. Accordingly, we used the surface site response relative to seismic basement (having Vs>2.5 km/s) of NIGH16 as a constraint in the inversion. This surface site response transfer function was calculated by using re-determined 1D velocity model of NIGH16, which was calibrated with observed surface-to-borehole spectral ratio.

Figure2 shows the result of inverted site responses located at the middle part of Niigata area shown in Fig. 1(b). The bold gray lines indicate the resultant site response from our inversion by using observed data. The site responses are commonly relative large in the frequency range of about 1.5-5 Hz, and decay significantly with the frequency increasing over about 5 Hz. Furthermore, the characteristics of high-frequency decay-rate are different at sites (e.g. Anderson and Hough [1984]).

Our inversion result also provides Q_s of path effect, which could be approximated with the relation $87.1*f^{0.98}$ shown in Fig. 3(a). Although our result of Q_s is relatively larger than the previous results used different data sets of the smaller distance range of r < 80km in this area, it corresponds with the distance-range dependence of dataset pointed out by such as Amaike et al. [2006]. Figure 3(b) illustrates the comparison of the seismic moments obtained from separated source spectra in our inversion with those from F-net by NIED. Both estimates were almost within a factor of 1.3. These properly results of path and source parameters suggest that the reliable site responses are derived from our inversion.

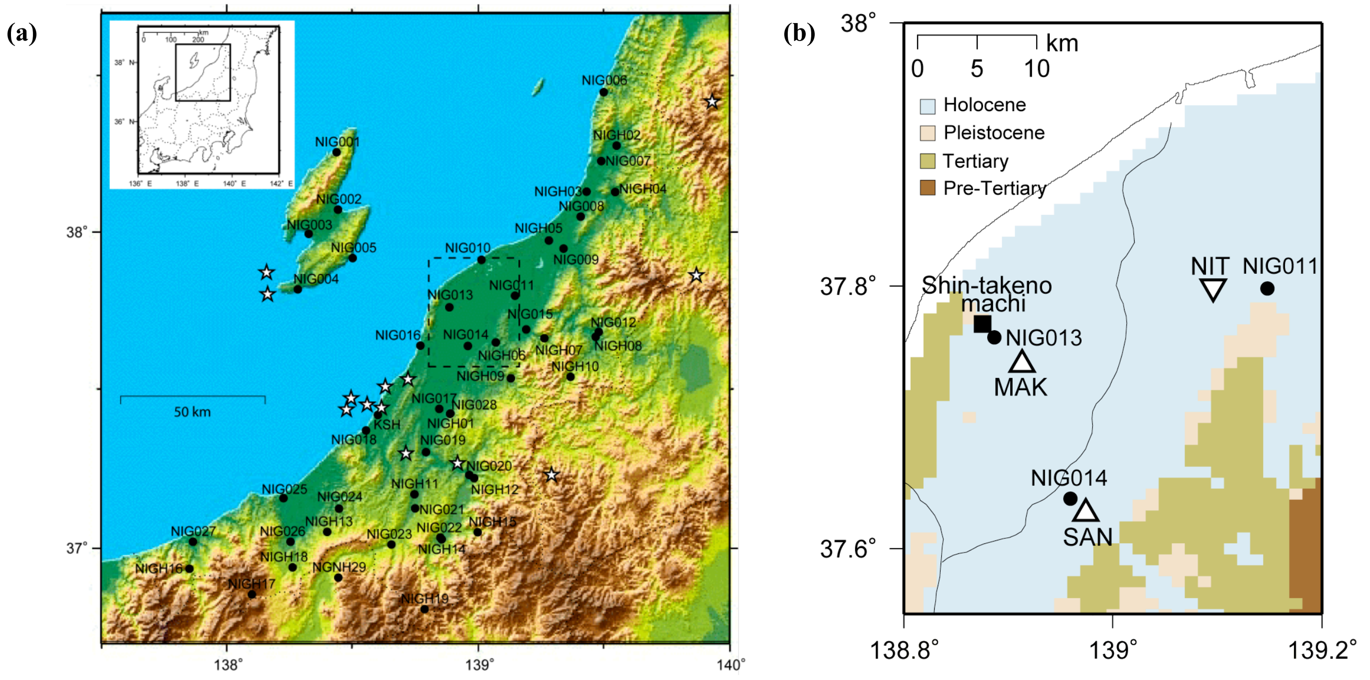

Fig. 1. (a) Geography of the Niigata area. Stars indicate epicenters of used events. Solid circles indicate earthquake observation station used in our inversion. (b) Locations of microtremor array explorations (triangles), earthquake observation stations (solid circles) and borehole (solid square) with surface geology (Wakamatsu et al[2005]) in the middle part of Niigata area shown by broken-line square in Fig.1(a)

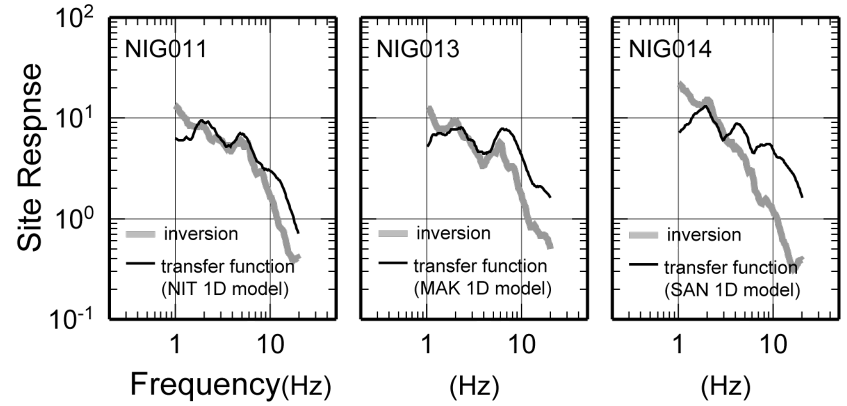

Fig. 2. Inverted site responses (bold gray lines) located at the middle part of Niigata area shown in Fig. 1(b) compared with transfer functions (thin-black lines) using nearby 1D layered velocity models based on microtremor array exploration.

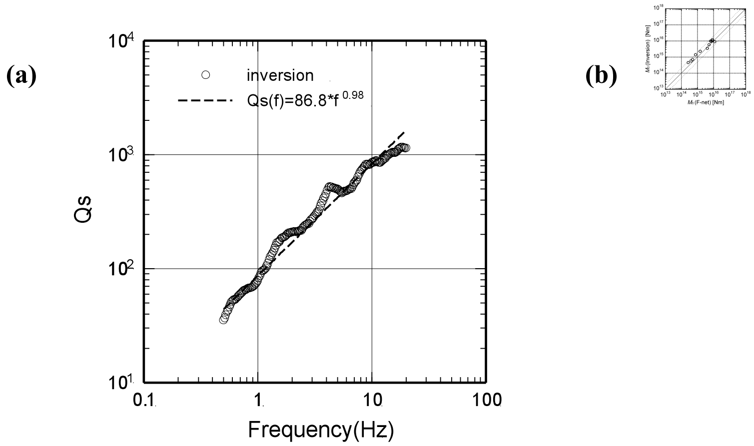

*Fig. 3. Separated path and source parameters by inversion. (a) Qs from our inversion. The line shows regression result by 87.1*f* $^{0.98}$. *(b) Comparison of seismic moments from this study with those from NIED.*

Comparison of site response with transfer function from 1D layered velocity model

Geophysical surveys by using vertical-component of microtremor array measurement have been conducted in Niigata area for estimating deep S wave velocity structure that aim to simulate long-period ground motion (e.g. Sato et al. [2009]). This method gives us the Rayleigh wave phase velocity, and then S wave velocity structure is derived from phase velocity inversion (e.g. Yamanaka et al. [2000]). Figure 4 shows the estimated deep 1D S wave velocity models at NIT, MAK and SAN by Sato et al. [2009] with shallow

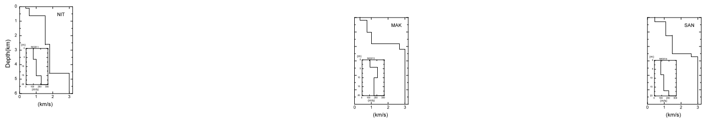

Fig. 4. 1D layered S wave velocity models at NIT, MAK and SAN by Sato et al. [2009]. Shallower part of models at each sites (within each figure) are provided from nearby K-NET station of NIG011, NIG013 and NIG014, respectively

models of 20 m depth provided by nearby each K-NET station of NIG011, NIG013 and NIG014, respectively. The site response transfer functions at NIT, MAK and SAN were calculated by using 1D deep layered velocity models with shallow models shown in Fig.4, and also displayed in Fig. 2 for the comparison with the estimated site responses at nearby each K-NET station of NIG011, NIG013 and NIG014, respectively. In the calculation of transfer functions, the damping factors ($h=Q_s^{-1}/2$) of each layers were given from the empirical regressions (Fukushima et al. [1994]). The soil damping factor in the empirical regressions were applied to the shallower part of 20 m depth of layers and the rock damping factor in the empirical regressions were applied to the deeper part of layers. From the comparison shown in Fig. 2, transfer functions of 1D layered velocity models based on microtremor array exploration are relatively larger in the frequency over about 3 or 6 Hz than the estimated site responses. This discrepancy in the high-frequency can point out that the 1D layered velocity models shown in Fig. 4 are not appropriate enough for the assessment of high-frequency site responses, because these models are only calibrated for the use of long-period ground motion simulation. Therefore, in the following section we investigate an another factor of a 1D velocity model by using the borehole log data, and show significant improvement in estimating high-frequency site responses by using a new 1D velocity model.

SITE RESPONSE BY 1D HETEROGENEOUS VELOCITY MODEL

Borehole-log data in the Niigata area

In Niigata area, geophysical borehole logging has been conducted by JNOC (Japan National Oil Corporation; the predecessor of JOGMEC) for the purpose of natural resources exploration. Figure 5(a) shows a sample of borehole-log of P wave velocity in the central part of the Niigata area presented by JNOC [1994]. The location of the borehole is also shown in Fig. 1(b) as Shin-takeno-machi. According to Fig. 5(a), we can find that the actual velocity structure in this area is strongly characterized by two factors of depth-dependence and random fluctuation. This finding may suggest that these two factors should be considered in the existing 1D velocity models of this area, for the better estimation of high-frequency site responses. However, although the depth-dependence of velocity is roughly represented by using five layered model increasing with depth, the random fluctuation is not considered in the 1D velocity models shown in Fig. 4 at all. Therefore, it can be seen that the random velocity fluctuation is one of the important key factor to enhance the existing 1D model's applicability in estimating high-frequency site responses. Thus, in the following section, to modify the existing 1D velocity models by using random velocity fluctuation, we investigate the statistical property of random fluctuation based on the borehole-log data.

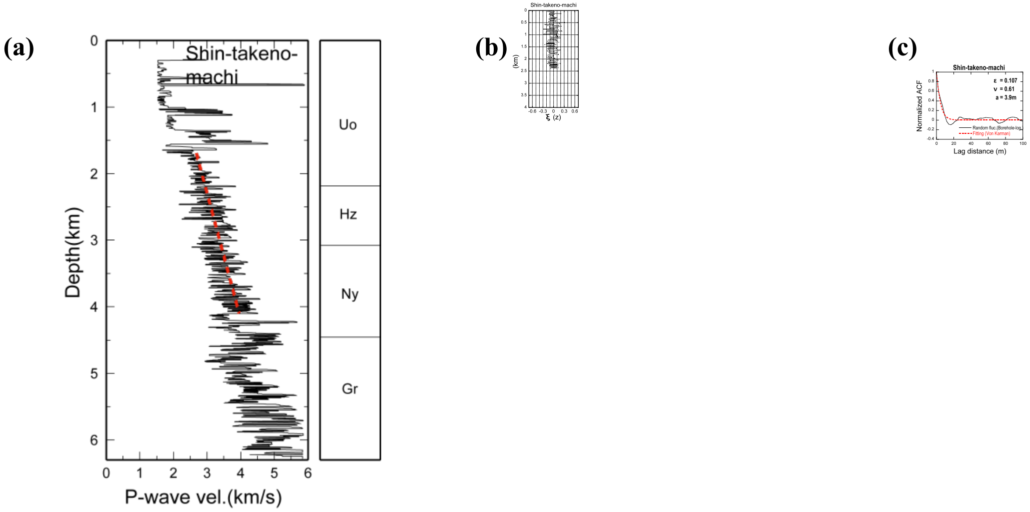

Fig. 5. (a) P wave velocity borehole-log with geological column at "Shin-takeno-machi" by JNOC. Broken red line indicates linear regression line for $V_p(z)$.In the geological column, Uo:Uonuma formation(Quaternary), Hz: Haizume formation(Quaternary); Ny: Nishiyama formation(Quaternary), Gr:Green tuff. (b) Dimensionless random-fluctuation data at Shin-takeno-machi derived from Eq.(1) by using borehole-log with depth range of 1.7 to 4.1 km. (c) Fitting result of the normalized auto-correlation function (ACF).

Statistical property of heterogeneity

The borehole-log data of P-wave velocity were digitized in this study at 2-m intervals using scanned paper documentation of JNOC [1994]. The procedure of estimating statistical property of random fluctuation is almost the same as previous study (e.g. Horike et al.[1991], Shiomi et al.[1997]). In this procedure, first of all, the dimensionless random-fluctuation data of $\xi(z)$ was extracted from the borehole-log data based on Eq.(1), as follows:

$$\xi(z) = [\, V_p(z) - (V_0 + V_1 \cdot z) \,] / (V_0 + V_1 \cdot z) \qquad (1)$$

where $V_p(z)$ is borehole-log data of P wave velocity, z is depth, $(V_0 + V_1 \cdot z)$ is the linear regression line for $V_p(z)$ (see Fig. 5(a) indicated by broken red line) determined from the least-squares method. Figure 5(b) illustrates the resultant random-fluctuation data used in the estimation of statistical property. The range of data used for regression analysis was determined from the stability of data. The next procedure calculates the auto-correlation function N(r) of random-fluctuation data. And then, the statistical-property parameters of heterogeneity are optimized to fit this correlation function by using the Von Karman-type correlation function. This correlation function is expressed as follows (e.g. Sato and Fehler [1997]):

$$N(r) = (\varepsilon^2\, 2^{(1-\nu)}) / (\Gamma(\nu))\, (|r|/a)^{\nu}\, K_{\nu}(|r|/a) \qquad (2)$$

where r is the lag distance, ε is the standard deviation of random-fluctuation, ν is the Hurst exponent, a is the correlation distance, Γ is the Gamma function and K_ν is the modified Bessel function of the second kind. The three parameters of ε, ν and a in Eq.(2) are optimized as the statistical-property parameters of heterogeneity by curve-fitting. Figure 5(c) illustrates the fitting result of the normalized auto-correlation function (ACF). The three estimated statistical-property parameters are also listed in Table 1.

Table 1. Statistical properties of random velocity fluctuation at Shin-takeno-machi

Site	Depth range of used data	Stratigraphy	Standard deviation ε	Hurst exponent ν	Correlation distance a (m)
Shin-takeno-machi	1.7(km)~4.1(km)	Quaternary	0.107	0.61	3.9

Site response from 1D heterogeneous velocity model

To improve a 1D velocity model's applicability in estimating high-frequency site responses around the Niigata area, from previous discussion, it is suggested that an existing 1D layered velocity model needs to be modified by taking into account a random fluctuation of velocity, such as so-called 1D heterogeneous velocity model. In this study, a 1D heterogeneous velocity model were constructed by adding the numerically generated dimensionless random fluctuations data of 1-m interval to the deeper part (> 20 m) of an existing 1D velocity model. The dimensionless random-fluctuation data were generated based on the Von Karman-type correlation function using three parameters of a, ν and ε, as the same methodology in our previous study [Sato and Yamanaka (2010)]. According to our previous study, it was also cleared that the parameter ε played major role in controlling the high-frequency decay-rate of transfer function using a 1D heterogeneous velocity model. Therefore, we examined performances of 1D heterogeneous velocity models (see Fig. 6) considering various parameter conditions of ε (ε=0.05, 0.1, 0.15) on estimating high-frequency transfer function. In generating dimensionless random-fluctuation data, the other parameters of the Von Karman-type correlation function were fixed by a=40 m and ν=0.4. Figure 7 illustrates the comparison of the estimated site response with the transfer functions using nearby 1D heterogeneous velocity models with various ε. And it was found that the high-frequency decay-rates of transfer functions are increasing with larger ε. The ε values in Fig. 7 to be in good agreement with the estimated site response are consistent with the estimated ε of nearby Shin-takeno-machi borehole-log data as shown in Table 1. This suggests that borehole-log data are useful for determination of ε in constructing 1D heterogeneous velocity models.

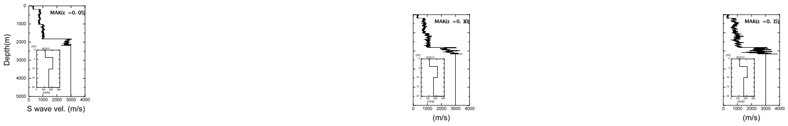

Fig. 6. 1D heterogeneous velocity models with various parameter conditions of ε (ε=0.05, 0.1, 0.15) based on MAK 1D layered model.

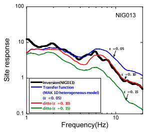

Fig. 7. Comparison of inverted site response (bold black lines) at NIG013 with transfer functions (thin lines) using 1D heterogeneous velocity models with various parameter conditions of ε (ε=0.05, 0.1, 0.15) as shown in Fig. 6.

EFFECT OF ADDITONAL DAMPING FACTOR ON SITE-RESPONSE ESTIMATION

The attenuation of seismic wave is mainly caused by scattering from multi-scale inhomogeneous media structure, and by absorption in intrinsic micro-mechanism of such as displacement across cracks and joints. Consequently, reduction of seismic amplitude is the most obvious effect from inhomogeneous media. Because the random-fluctuation of velocity, as seen in a borehole-log, reflects inhomogeneous media structure including cracks and fractures (e.g. Sato and Fehler [1997]), it seems reasonable to suppose that the parameter ε of 1D heterogeneous velocity model (so-called the heterogeneity parameter ε) may be related to a damping factor of 1D layered velocity model. Therefore, we examined the effects of various additional damping factor (frequency-independent) h^{add} (h^{add}=0.001, 0.005, 0.01) on high-frequency transfer function by using the 1D layered velocity models shown in Fig.4. In this calculation, the additional damping factors were added to the deeper part (< 20 m) of layers, similar to the above examination using the heterogeneity parameter ε. Figure 8 illustrates the comparison of the estimated site response with the transfer functions using 1D layered velocity model with various additional damping factors. From Fig.8, the high-frequency decay-rates of transfer functions are increasing with larger h^{add}, which is similar to the effects of the heterogeneity parameter ε on the high-frequency decay-rates of transfer functions. These results of our examination show that the heterogeneity parameter ε is strongly related to the damping factor of 1D layered velocity model. Furthermore, it may follow from these results that the observed high-frequency decay-rates of site responses are controlled by the strength of heterogeneity of underground structure (e.g. Abercrombie [1997]).

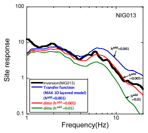

Fig. 8. Comparison of inverted site response (bold black lines) at NIG013 with transfer functions (thin lines) using 1D layered velocity models with various additional damping factor of h^{add} (h^{add}=0.001, 0.005, 0.01).

SUMMARY

In this study, it was examined whether the site response transfer functions using 1D layered velocity models based on microtremor array exploration would be possible to explain the estimated short-period site responses using observed earthquake records or not. As a result, the site response transfer functions were relatively larger in the frequency over about 3 or 6 Hz than the estimated site responses. According to deep borehole-log in the Niigata area, the actual velocity structure was strongly characterized by two factors of depth-dependence and random fluctuation. Therefore, to improve a 1D velocity model's applicability in estimating high-frequency site responses, we proposed to modify an existing 1D layered velocity model by taking into account a random fluctuation of velocity, so-called 1D heterogeneous velocity model. Consequently, it was demonstrated that the high-frequency decay-rates of transfer functions using 1D heterogeneous velocity models, which were superposed a numerically generated dimensionless random-fluctuations data on 1D layered velocity models, were increasing with the larger heterogeneity parameter ε, and the site response transfer functions using 1D heterogeneous velocity models with the proper heterogeneity parameter ε could well explain the high-frequency decay of the estimated site responses. Besides, the ε values to be in good agreement with the estimated site response are consistent with the actual ε derived from nearby borehole-log data. Furthermore, we examined the effects of various additional (independent-frequency) damping factor h^{add} on estimating high-frequency transfer function by using the 1D layered velocity models, because the reduction of seismic amplitude is the most obvious effect from random fluctuation. Accordingly, the high-frequency decay-rates of transfer functions were increasing with larger h^{add}, which is similar to the effects of the heterogeneity parameter ε. Finally, we were concluded that the heterogeneity parameter ε was strongly related to the damping factor of 1D layered velocity model, and that the observed high-frequency decay-rates of site responses might be controlled by the strength of heterogeneity of underground structure.

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