Incorporating the Gradual Increase of Velocity with Depth into Modeling 3D Velocity Structures of the Kanto Basin

Takashi. HAYAKAWA[1], Bunho. KOJIKA[2]

[1] *Research Engineer, SHIMIZU Corporation, Tokyo, Japan*
[2] *Researcher, Ohsaki Research Institute, Inc, Tokyo, Japan*
Email: takashi.hayakawa@shimz.co.jp

ABSTRACT :

Recently site response by using the data observed at very dense array was obtained in the Tokyo Metropolitan area. Site responses of S-wave portion in the period range for 1-2 sec show drastic changes even in a closed distance. Because strong ground motions in the period range of several seconds are main cause of damages to various buildings, such spatial variation of site responses should be considered for the seismic design of buildings. In this study, we developed the method to reflect the site response for 2-4 sec obtained by the spectral inversion analysis on the 1D velocity structure. Resultant 1D structures by using this method allow us to develop 3D velocity structures for predicting strong ground motions in period range of several seconds.

KEYWORDS: Ground Motion Prediction, Kanto basin, Modeling of Velocity Structure, Period Range of Several Seconds

1. INTRODUCTION

Recent site response (effects of sediment layers on the ground motions) studies for the broad area by using observed data obtained from the dense accelerograph network, such as the Tokyo Metropolitan area, revealed that site responses of S-wave portion in the period range for 1−2 sec vary drastically (Tsuda, 2007). Because the ground motions of that period range are very critical for the seismic design for various kinds of buildings, understanding the characteristics of spatial variation of site response is very important for the ground motion prediction in the Tokyo Metropolitan area.

Because the strong ground motions observed on the Tokyo Metropolitan area include body waves as well as surface waves, both waves should be modeled properly for the ground motion prediction for several seconds. Especially to modeling surface waves on this area, surface waves have been amplified based on the 1D velocity structure similarly to those for S-wave and affected by the all propagation path around the Kanto area. These features of surface waves indicate that the 3D velocity structure which can represent the observed spatial variation of site response for S-wave properly is necessary for modeling surface waves on this area. Even though several 3D velocity structures for the ground motion prediction on the Kanto area (Tanaka *et al.*, 2005, Yamanaka and Yamada, 2006) have recently been proposed, no 3D velocity structure that reflects the observed spatial variation of site response for S-wave for several seconds and is suitable for the ground motion prediction for several seconds is available.

However, because very high possibility for occurring the large earthquake (its magnitude is around 7) on Tokyo Metropolitan area has already been released (Subcommittee for long-term evaluations, Earthquake research committee of Japan, 2004), constructing the three-dimensional velocity model suitable to predict ground motions in period range for several seconds is the urgent issue for ground motion prediction in the Tokyo Metropolitan area.

2. BASIC IDEA TO CONSTRACT VELOCITY MODEL AND INVESTIGATIONS IN THIS STUDY

For layers deeper than several hundreds of meters under the Kanto plane, the detailed P-wave structures were surveyed by the acoustic logging and VSP profiling (Yamamizu, 2004). These surveys showed that the P-wave velocity is proportional to the depth and the P-wave velocity is almost only the function of the depth on the Kanto area. The sediment layer of the Kanto area can be partitioned into roughly three strata (Suzuki, 1996), Miura-layer (just above seismic bedrock), Kazusa-layer and Shimousa-layer. Applying the relation between the depth of sediment layers (Miura-layer and Kazusa-layer) (Hayakawa *et al.*, 2006) and P-wave velocity to the distribution of depth for each layer (Suzuki, 1996) allows us to model 3D structures of P-waves for deeper than several hundreds of meter. Because S-wave velocity correlates well with the P-wave velocity, the 3D structures of S-waves can be estimated via empirical relation for P- wave.

The velocity structures for P-wave as well as S-wave shallower than several hundred meters have been obtained by VSP profiling and array analysis of the microtremor data at several points. This shallow velocity structure plays an important role for the S-wave amplifications for several seconds based on the one-quarter wavelength low. However, there is no data of the detailed shallow velocity structure that is possible to reproduce the complex spatial variation of site response of S-wave for several seconds based on the observed data. So far, the spatial distribution of site response of S-wave for several seconds itself is the most effective information to model the velocity structure for several hundred meter depths.

The recent reflection surveys for the Tokyo Metropolitan area revealed 1D the velocity structure of P-wave at many points. Having S-wave 1D velocity structure based on these velocity structures of P-wave might have the possibilities to derive the statistical relations between the features of 1D velocity structures at the Tokyo Metropolitan area with the site response of S-wave. These relations allows us to estimate the 1D velocity structures at many points based on the spatial distribution of site response of S-wave for several seconds and then construct the 3D velocity structures.

Based on these features, the basic idea to estimate 1D velocity structures for the purpose of constructing 3D velocity structures on the Kanto plain suitable to ground motion prediction for several seconds is the following.

Step1) Construct the average structure

The sediments above seismological basement assume to have two layers whose boundary is the top depth of Miura layer. For the deeper layer, the empirical relation between depths with P-wave velocity in Miura-layer is applied to construct the P-wave 1D velocity structure and then the S-wave 1D velocity structure is determined based on the relation between P-wave and S-wave velocity. For the upper layer, the similar relations for the Kazusa-layer have been applied to construct the P-wave as well as S 1D velocity structure. The 1D structure deeper than several hundred meters is reasonable because locality is weak in such depth. – However the shallow structure is the averaging structures on the Kanto plain without the locality that can reproduce the site response of S-wave for several seconds.

Step2) Modifying the structure to fit the site response

The shallow structure of several hundred meters depth of the average structure obtained in the previous step is modified to fit the site response of S-wave based on the observed data.

In this study, we developed the method of incorporating the site response in the average structure made in Step1. This method is applied for Step2. The P-wave 1D structures have been obtained by the reflection surveys on Tokyo Metropolitan area. We could derive valid S-wave 1D structures from P-wave 1D structures at these points and calculated the theoretical site response of S-wave.

We modeled the P-wave velocity of several hundred meters depth based on the following linear regression curve at each point.

$Vp = a * Z+b$,

where Vp is P-wave velocity [m/s] and Z is the depth [m].

We derived the statistical relations between the regression coefficients a, b with the theoretical site response of S-wave.

We confirmed the availability of resultant statistical relations. We constructed the average structures by the same manner in Step1 at the points where S-wave structures were derived. And then, using the statistical relations, we modified the shallow structure to fit the site response at each point. We calculated the site response of the modified average structures and make sure that they can be reproduced.

3. STATISTICAL RELATIONS BETWEEN CHARACTERISTICS OF VELOCITY STRUCTURES AND SITE RESPONSES IN THE PERIOD RANGE OF SEVERAL SECONDS

3.1 Surface Layers which Affect Considerably Site Responses in the Period Range of Several Seconds

We have investigated the effect of surface geology on a site response with several seconds for S-wave at KiK-net KOTO(TKYH11). The detail velocity structures that got the validation by 1-D wave propagation simulation have already been estimated (Hayakawa, 2006). We show the location of the site and the structure of S-wave has been shown in Figure 2. After we constructed the velocity structures with perturbing 20 % for S waves up to the depth D, we calculated the variation ratio C of site response of S-waves for each mode based on the following equation

$$C^m(D) = \frac{S_-^m(D) - S_+^m(D)}{S^m} \qquad S^m = \int_{fm-fd}^{fm+fd} abs(H(f))df$$

$$S_-^m(D) = \int_{fm_- - fd}^{fm_- + fd} abs(H_-(f,D))df \quad , \quad S_+^m(D) = \int_{fm_+ - fd}^{fm_+ + fd} abs(H_+(f,D))df \qquad 1)$$

Where H_- and H_+ are the transfer function between surface/seismic bedrock (each subscription denotes the 20% increasing S-wave velocity above the depth D (+), and 20% decreasing (-). The subscriptions for S and f_m mean the same as H. f_m is period of *m*th mode. Also f_d denotes the width of period to calculate the mean transfer function and is set to 0.15 Hz to include the peak of amplification.

We show the D as a function of C and the shape of 1st, 2nd, and 3rd mode in Figure 4 (TKYH11). The depths that maximize the C exist for each mode. The site response for each mode depends on the structure of the certain depth and the depths with maximum C agree with the depth of the shallowest node for second mode or higher. We abbreviate that depth Dm(j), where j corresponds to the order of mode. Because the depth of the seismological basement is deeper than 1.5 km on Tokyo Metropolitan area, the 2-4 sec periods corresponds to the predominant periods of the second or third order. Thus, the site response with 2-4 sec periods is strongly affected by the structure up to the depth of Dm(2) or Dm(3).

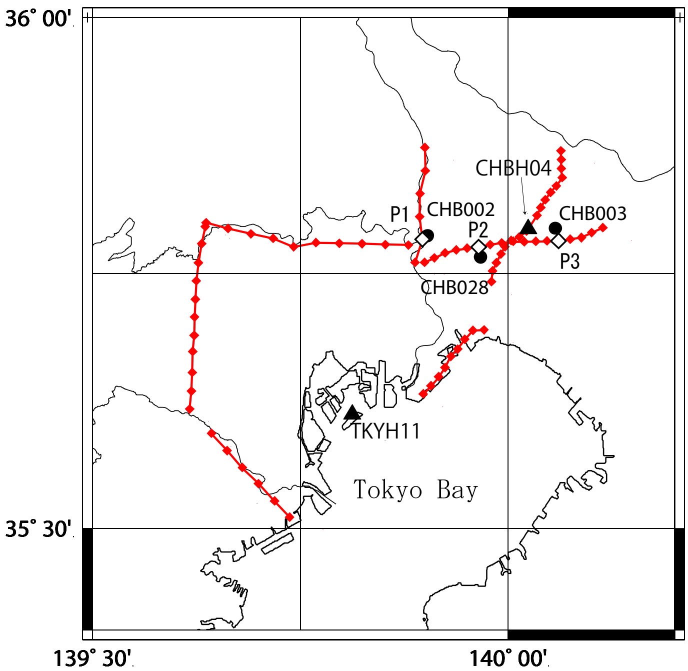

Figure 1 lines of reflection survey (solid line), target points for estimating 1D S-wave velocity structure (diamond) and observation sites (circle and triangle)

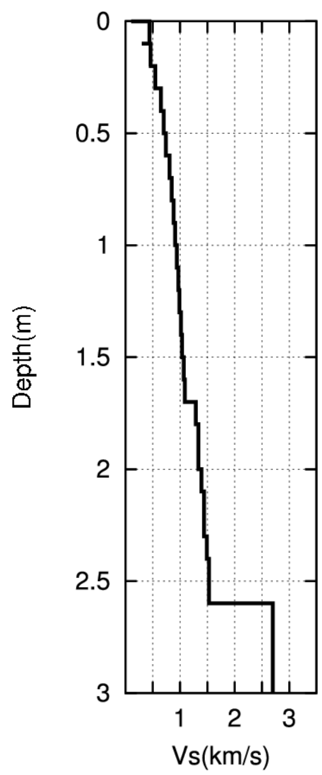

Figure 2 S-wave Velocity Structure at TKYH11

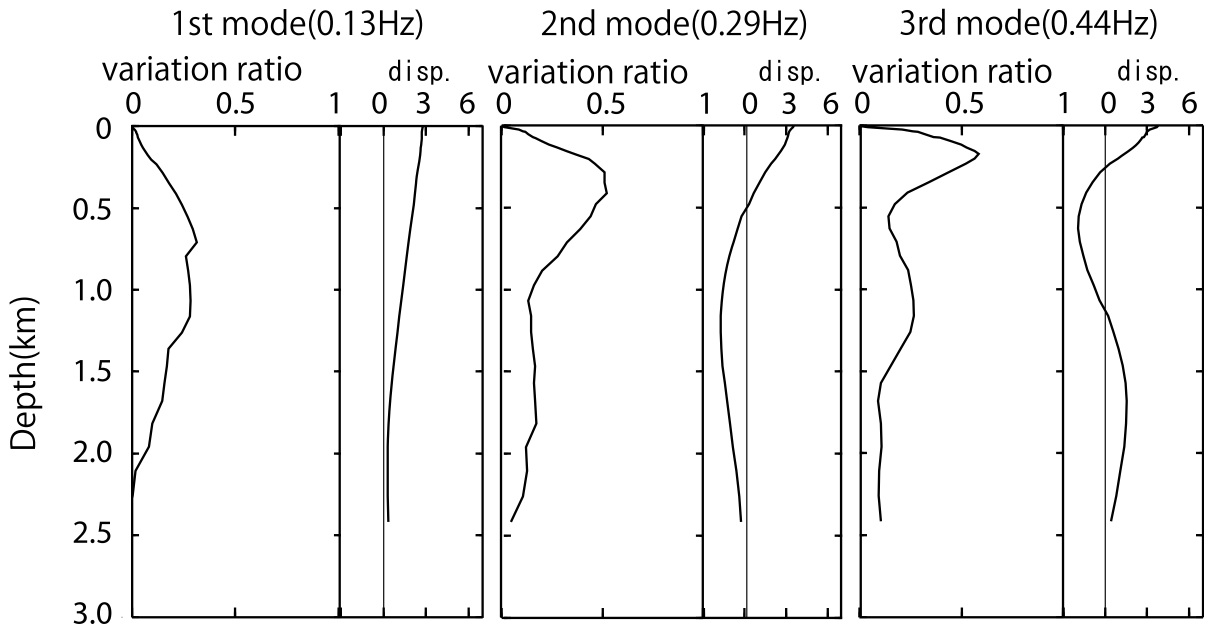

Figure 3Variation rates of S-wave amplifications and vertical displacement distributions of 1st, 2nd and 3rd modes at TKYH11

3.2 1D S-wave velocity structures in the Tokyo Metropolitan area

In order to detect the statistical features of the velocity structures, 1D velocity structures to the seismological basement at several kinds of sites is necessary, but the number of data for these structures is very small. Recently the velocity structures of P-wave for sediments and around the depth of seismological basement have been obtained by many studies of reflection surveys investigated around the Tokyo Metropolitan Area(Chiba Pref., 1998,1999,2000, Tokyo Metropolitan, 2004, Kawasaki City, 2000). The 1-D structures of S-wave have been derived based on the P-wave structures obtained by those reflection surveys by using the following relations.

$$Vs=0.9Vp-1.08 \quad (\text{for } Vp<2.6\text{km/s}) \qquad 2)$$
$$Vs=Vp/2.14 \quad (\text{for } 3.6\text{km/s}>Vp>=2.6\text{km/s}) \qquad 3)$$
$$Vs=Vp/1.83 \quad (\text{for } Vp>=3.6\text{km/s}) \qquad 4)$$

Equation 2 was obtained from the data by PS loggings and the other seismic explorations in the Tokyo Metropolitan area (Chiba Pref., 1998). Equation 3 and 4 were average relations recognized in such data and were set in this study. The points where S-wave 1D structures were derived have shown in Figure 2. To confirm the derived velocity structures for several seconds, we compared the ratio of observed amplitude spectrum between surface and borehole records obtained at the closed K-NET and KiK-net stations for each point and theoretical 1D transfer functions at each point. We compared at P1, P2 and P3. The P-wave velocity structures for each point is shown in Figure4. Even though the surface records come from the KiK-net site closed to each point, the borehole records come from CHBH04. This site has a borehole instrument locating on the seismological basement with S-wave velocity ≧ 3.0 km/s. The spectral ratio are calculated from 10 events that those focal depths are deeper than 45 km as well as those magnitude (Mj) are larger than 4.5. The components of body wave can be predominant for these events. After we calculate the averaged spectral ratio for each horizontal component, the ratio is smoothed over 0.1 Hz by using Parzen window. We show the comparison of observed spectral ratio with the theoretical transfer functions for each point. The good agreement of theoretical transfer functions with the observed spectral ratio around 2-4 sec is suggesting the validity of our estimated velocity structures.

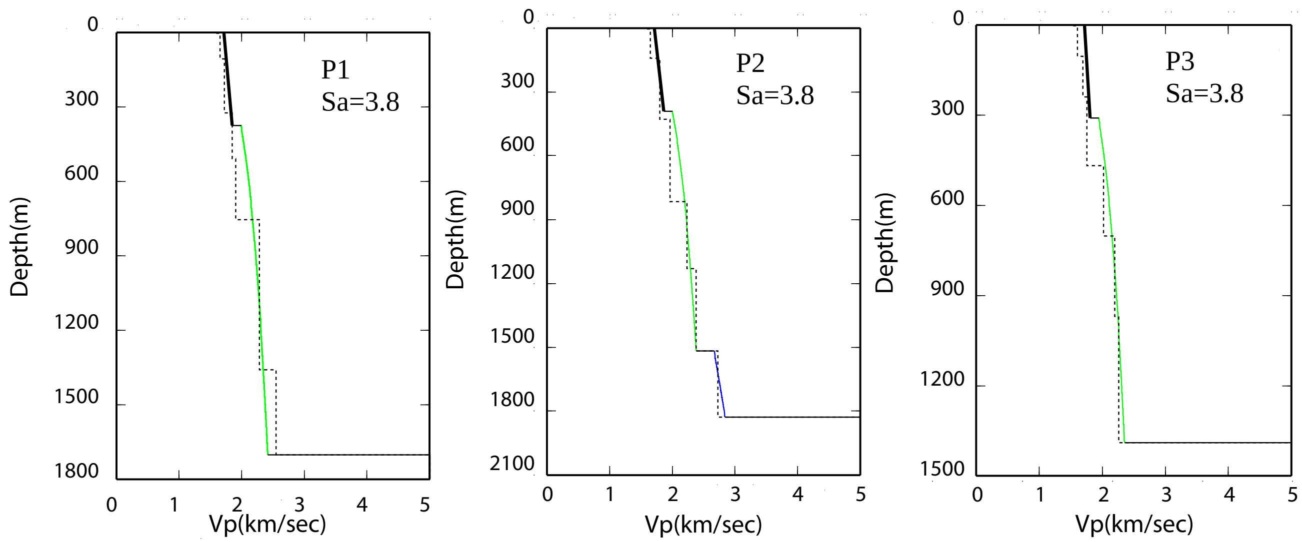

Figure 4 P-wave velocity structures obtained by reflection surveys(dashed line) and modified average structures (solid line) at P1 P2 P3

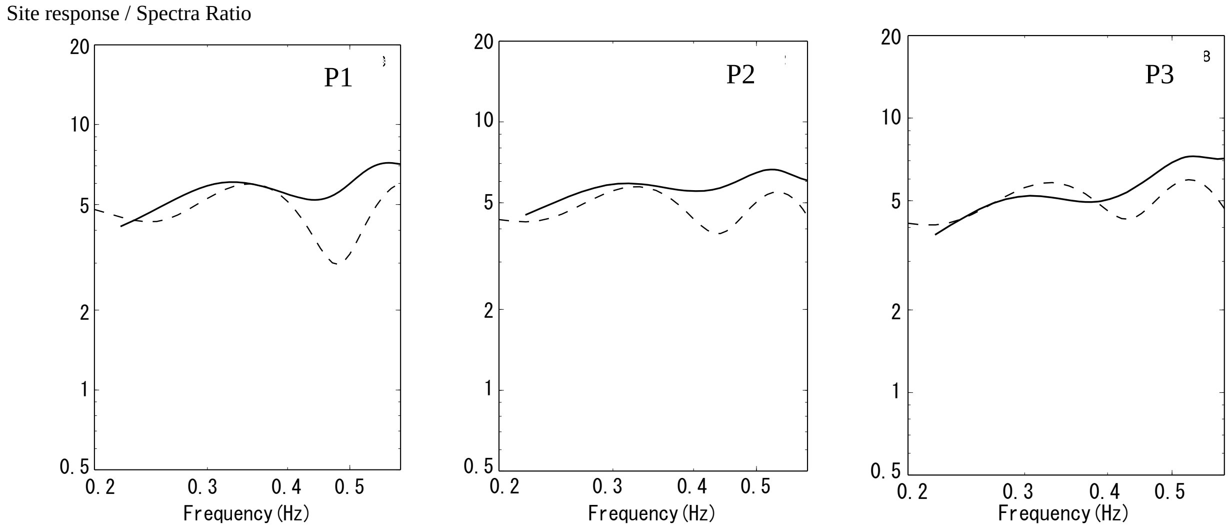

Figure 5 Comparison of theoretical site responses(dashed line) and observed spectral ratio(solid line) at P1 P2 P3

3.3 Statistical Relations between Characteristics of Velocity Structures and Site Responses in the Period Range of Several Seconds

The depth that effects the ground motions for 2-4 sec, De has been derived based on the following relation by using the S-wave structures estimated in the previous section

De= Dm(3)+(Dm(2)-Dm(3))*(0.33-f3)/(f2-f3)   5)

This means that De corresponds to the linear-interpolation between the depth of Dm(2) and Dm(3) at 0.33 Hz. Frequency f2 and f3 correspond to the predominant frequency of 2nd and 3rd mode, respectively. The results of geophysical surveys (eg.VSP profiling) on the Tokyo Metropolitan area showed that the P-wave velocity is simply proportional to the depth even for the shallow structures. The velocity structure of P-wave to the depth De has been derived by the following linear regression curve

Vp=a*Z+b (Z<= De)   6)

Where Vp is P wave velocity [m/s], Z is the depth from the surface [m].

We define the site response Sa by following equation.

$$Sa = \int_{0.25}^{0.5} abs(H(f))df \qquad 7)$$

Sa is averaged transfer function for 2-4 sec. Sa of each S-wave model estimated in previous section is shown as a function of b in Figure6. The regression curve for b as a function of Sa is the following. This regression curve is also plotted in Figure 6.

$$b=-59Sa+1893 \qquad 8)$$

This relation indicates that bigger site response is getting smaller P-wave velocity on the surface. Constant a as a function of b is shown in Figure 7. The regression analysis for a as a function of De and b got the following curve

$$a=5.23-0.0030b+0.00090De \qquad 9)$$

The averaged site response for 2-4 sec allows us to estimate the 1D structure of P-wave to the depth De by using equation (8) and (9). Then 1D the structure of S-wave has been derived by using equation (2), (3), and (4).

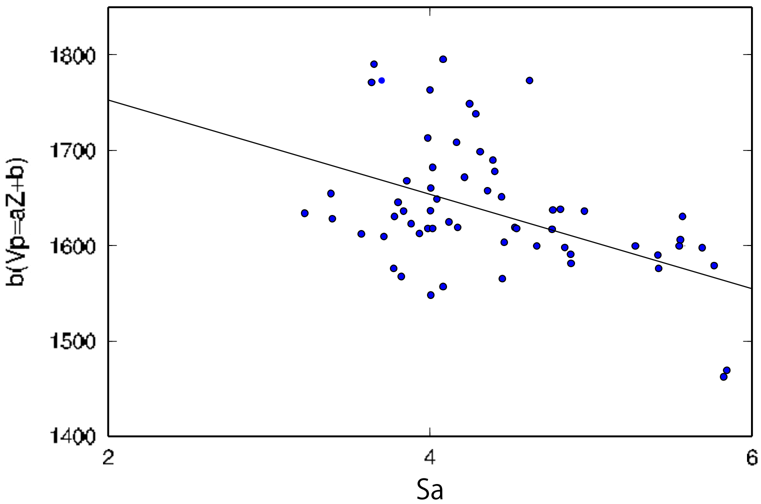

Figure 6 Relation between site responses Sa and regression coefficients b

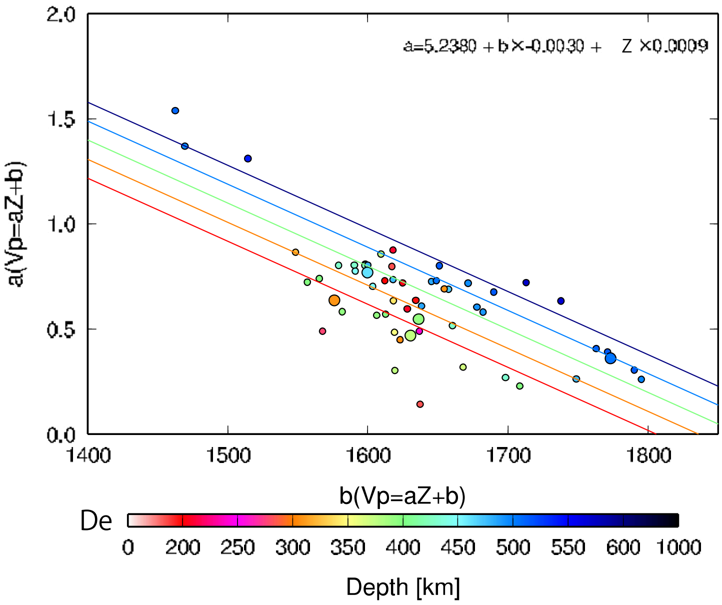

Figure 7 Relation between regression coefficients a and b

4. AVAILABILITY OF STATISTICAL RELATIONS IN MODELING VELOCITY STRUCTURE

The structures of P-wave velocity have been derived at points where we derived the S-wave structures in section 3.2 by using the following two equations (Hayakawa, 2006).

$$Vp=0.931Z^{0.128} \quad \text{for} \quad Z < Z_d \quad (10)$$
$$Vp=0.226Z^{0.337} \quad \text{for} \quad Z_d < Z \quad (11)$$

Where Zd is the upper depth of Miura-layer.

These equations represent the empirical relation of depth with P-wave velocity in Miura and Kazusa-layer and can be used to construct an average P-wave structure in the Tokyo Metropolitan area. Minimum P-wave velocity of Kazusa-layer is about 1.88km/s. P-wave velocity is assumed to be constant, 1.88 km/s if the P-wave velocity is smaller than 1.88 km/s in equation (10). We used the top depth of seismic bedrock and Miura-layer estimated by the reflection surveys. Then we constructed the velocity structures of S-wave based on the equations (2), (3), and (4). This is Step1 in Chapter2. The P-wave and S-wave velocity structures derived from the reflection surveys in the previous section are called the original P-wave model and the original S-wave model, respectively. Also we call the velocity model constructed in the current section for P-wave and S-wave as the average P-wave model and average S-wave model, respectively.

The shallow part for average model has been modified to fit the Sa of the each original S-wave model by using the statistical relations (5), (8) and (9). This is Step2 in Chapter2. For example, the modified average P-wave model at P1, P2 and P3 were shown in Figure 4 as well as the original P-wave model.

If Sa of original S-wave models were reproduced in modified average S-wave models, statistical relations (5), (8) and (9) were thought efficient in modeling a 1D velocity structure from Sa. We plotted the site response for S-wave based on the original model in the horizontal axis and site response based on the modified model in the vertical axis in Figure 8. Both site responses are distributed close to the line of 1:1, suggesting that the site response based on the original model is well reproduced.

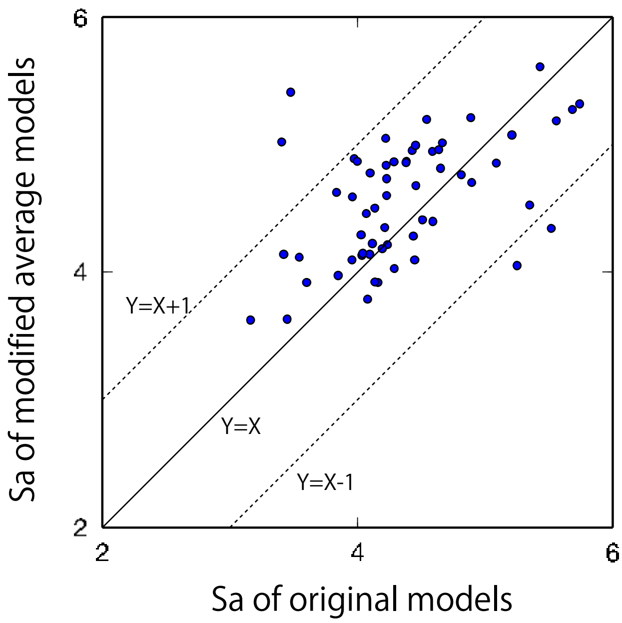

Figure 8 Site response Sa of original models and modified average models

5 CONCLUSIONS

The statistical relation of averaged site responses of S-wave for 2-4 sec period with the feature of velocity structures shallower than several hundred meters on the Tokyo Metropolitan area have been derived. The reproduction of site response for S-wave at many points based on the estimated velocity model indicates that the statistical relation derived in this study is effective to estimate the velocity structure.

Constructing the 3-D structures valid for several seconds by using the spatial distribution of site response for S-wave based on the observed records is future work.

ACKNOWLEDGMENTS

We thank Dr. K. Tsuda at SHIMIZU Corporation. We were really helped by his advices in writing this paper. We also thank Dr. H. Yoshida at SHIMIZU Corporation. We used his code in calculating S-wave transfer function. The records of K-NET, KiK-net were used in this study. K-NET and KiK-net are strong motion observation network managed by the National Institute for Earth Science and Disaster Prevention, Japan. We thanks to the effort of maintenance and data distribution.

REFERENCES

Chiba pref.,(1998) Report of underground structure survey results in Chiba, http://www.hp1039.jishin.go.jp/kozo/Chiba3frm.htm, (in Japanese)

Chiba pref.,(1999) Report of underground structure survey results in Chiba, http://www.hp1039.jishin.go.jp/kozo/Chiba4frm.htm, (in Japanese)

Chiba pref.,(2000) Report of underground structure survey results in Chiba, http://www.hp1039.jishin.go.jp/kozo/Chiba5frm.htm, (in Japanese)

Hayakawa, T. and Sato, T.(2005) Modeling 3D velocity structure of the Kanto basin considering gradual velocity increase with depth in the sediments, Proceedings of Annual Meeting of AIJ, 183-184

Hayakawa, T. and Sato, T.(2006) Study on modeling velocity structure for prediction of strong ground motions in short period range, Report of Special Project for Earthquake Disaster Mitigation in Urban Areas (DaiDaiToku project), 441-447

Kawasaki city(2000) Report of underground structure survey results in Kawasaki , http://www.hp1039.jishin.go.jp/kozo/Kawasaki3frm.htm, (in Japanese)

Tsuda, K. (2006) A New Method of Site Response Estimation and Its Application to Grand Motion Prediction, Ph.D. Thesis, Dept. of Earth Science, University of California, Santa Barbara

Subcommittee for long-term evaluations, Earthquake research committee of Japan (2004) "long-term evaluations of earthquakes along Sagami-Trough", http://www.jishin.go.jp/main/chousa/04aug_sagami/index.htm (in Japanese)

Suzuki, H.(1996) Geology of the KOTO Deep Borehole Observatory and Geological Structure beneath the Metropolitan Area, Japan, Report of the National Research Institute for Earth Science and Disaster Prevention, Vol56,77-123 (in Japanese with English abstract)

Tokyo Metropolitan,(2004) Report of underground structure survey results in Tokyo Metropolitan, http://www.hp1039.jishin.go.jp/kozo/Tokyo9frm.htm, (in Japanese)

Yamamizu, F. (2004) Seismic wave velocity structures in Kanto area as revealed by the crustal activity observation well VSP (in Japanese with English abstract)

Yamanaka, H., Yamanada, N. (2006) Modeling 3D S wave velocity structure of Kanto basin for estimation of earthquake ground motion, BUTURITANSA, Vol.59,No.6, 549-560(In Japanese)

Tanaka, Y. , Koketsu, K., Miyake, H., Furumura, T., Sato, H., Hirata N., Suzuki, H., Masuda, T.(2005) The Daidaitoku community model of the velocity structure beneath the Tokyo metropolitan area (1), Japan Earth and Planetary Science Joint Meeting, S079-P010(in Japanese)