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A proposal for a standard procedure of modeling 3-D velocity structures and its application to the Tokyo metropolitan area, Japan

Kazuki Koketsu [a,*], Hiroe Miyake [a], Afnimar [b,1], Yasuhisa Tanaka [a]

[a] Earthquake Research Institute, University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan
[b] Department of Geophysics and Meteorology, Bandung Institute of Technology, Bandung, Indonesia

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ABSTRACT

Most metropolitan areas are located over large-scale sedimentary basins. Since the sediments filling basins amplify ground motions and their velocity structures complicate the propagation of seismic waves, it is important for the prediction of strong ground motion and seismic hazard to determine the three-dimensional (3-D) velocity structures of these urban basins. This importance motivated various organizations to carry out extensive geophysical experiments and geological investigations, and velocity structure models are being constructed all over Japan. However, a study of a single dataset cannot completely define a 3-D velocity structure, so that we propose a standard procedure for modeling the 3-D velocity structure of an urban basin in Japan, by simultaneously and sequentially using various kinds of datasets such as those from refraction/reflection experiments, gravity surveys, surface geology, borehole logging, microtremor surveys, and earthquake records. We then apply the procedure to the Tokyo metropolitan area (TMA) over the Kanto basin with an area of about 17,000 km^2 and the maximum thickness of about 4 km. As one of the steps in the procedure, a joint inversion of refraction and gravity data has been formulated to determine the 3-D topography of interfaces of the sedimentary layers as well as lateral distribution of the basement slowness. We validate the constructed velocity structure model by comparison of observed and synthetic waveforms, since this modeling is carried out mainly for strong ground motion prediction. The proposed procedure including the joint inversion and validation with ground motion simulations works well for TMA, and the applicability of the standard procedure has been confirmed for regions with substantial data of experiments and earthquake records in Japan.

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1. Introduction

Most metropolitan areas are located over large-scale sedimentary basins. For example, Tokyo, the capital city of Japan, and its metropolitan area are located in a large-scale sedimentary basin called the Kanto basin with an area of about 17,000 km^2 and the maximum thickness of about 4 km. The basement rocks are exposed in the Kanto, Tanzawa, Ashio and Yamizo mountains, which surround the basin on the west and north sides as shown in Fig. 1. It is mostly bounded by the Pacific ocean on the other sides as well, so the structure of the Kanto basin is three-dimensionally complicated. The basin and its surrounding areas are seismically active regions, where the Philippine Sea plate subducts under the continental plate and the Pacific plate underthrusts beneath the Philippine Sea plate. The damage in the Tokyo metropolitan area (TMA) itself from the 1923 Kanto earthquake, in Mexico City from the 1985 Michoacan earthquake, and in the Marina district of San Francisco from the 1989 Loma Prieta earthquake has clearly illustrated the risks for population centers located in basins (e.g., Olsen et al., 1995). The sediments filling the basins amplify ground motions and their structures complicate the propagation of seismic waves (e.g., Koketsu and Kikuchi, 2000), so it is important for the prediction of strong ground motion and seismic hazard to determine the three-dimensional (3-D) velocity structures of these urban basins.

This importance motivated extensive refraction experiments carried out in and around the Kanto basin from 1975 to 1988. Koketsu and Higashi (1992) compiled the traveltime data from the experiments and inverted them to recover the topography of the sediment/basement interface in the basin. Komazawa and Hasegawa (1988) compiled the results of gravity surveys, and recovered this topography using Bouguer anomalies. Suzuki (1996, 1999) collected geological sections and velocity logging data at deep boreholes for constructing a 3-D velocity structure model. Yamanaka and Yamada (2002) compiled the results of microtremor surveys including their own observations for determining the 3-D velocity structure of the shallow sediments. They also constructed the velocity model for the southernmost part of Fig. 1 using the results of Nishizawa et al. (1996). These investigations

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[*] Corresponding author.
E-mail address: koketsu@eri.u-tokyo.ac.jp (K. Koketsu).

[1] Afnimar has only a single name according to the custom in Kalimantan, Indonesia.

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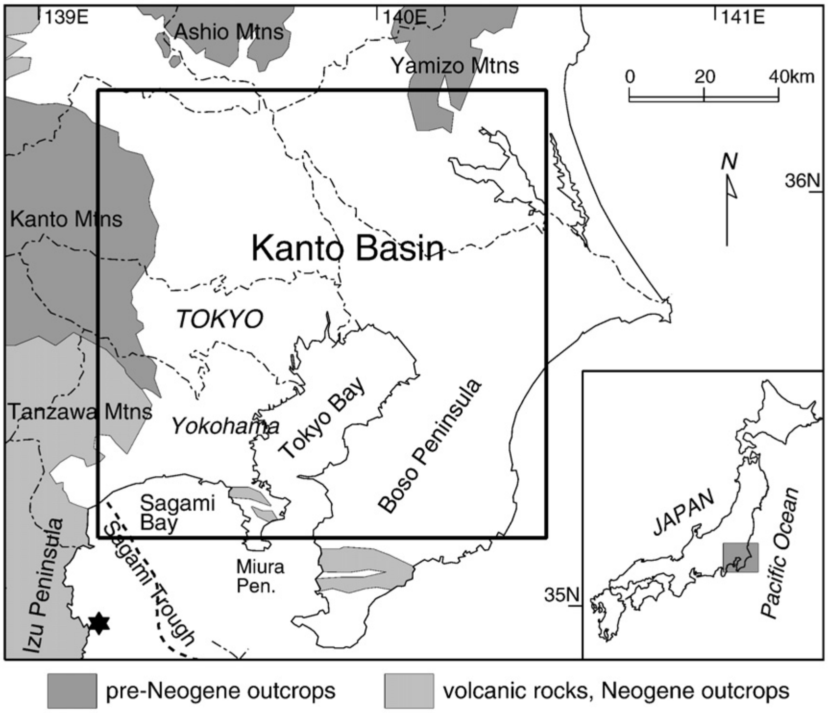

Fig. 1. Index map of the Kanto basin. The Pre-Neogene basement (dark), and the Neogene basement or volcanic rocks (light) outcrop in the grey zones, outlining the Kanto basin (Sugiyama et al., 1997). The rectangle drawn by thick lines is the 120 × 120 km target area of this study. The hexagram denotes the epicenter of the east off Izu peninsula earthquake in 1998.

are summarized that suggest three sedimentary layers in the Kanto basin and the total thickness of the sediments to be larger than 2 km in the region from the center to the northwestern part of the basin.

However, these studies cannot completely define the 3-D velocity structure. Koketsu and Higashi (1992), for example, noted that some model regions suffer ray coverage problem due to the irregular distribution of refraction data. We can overcome this problem by introducing the denser gravity data and jointly inverting them with the refraction data. Refraction data have the ability to resolve velocity structures in detail (e.g., Hole et al., 1992; Zelt and Borton, 1998) and precisely estimate seismic velocities and layer geometry (e.g., Zelt and Smith, 1992), but seismic surveys are too expensive to cover the whole area of a sedimentary basin. On the other hand, gravity surveys can be carried out more densely and homogeneously because of their portability, but they cannot measure seismic velocity directly, and the inversion of gravity data holds the inherent non-uniqueness of any geophysical method based upon a static potential field (e.g., Vigneresse, 1977). Afnimar et al. (2002) have developed a joint inversion scheme of refraction and gravity data for the 3-D shape of a sediment/basement interface assuming a relation between densities and seismic velocities. They showed that the joint inversion produces a better result than single-dataset inversions in its application to the Osaka basin, southwestern Japan. Parsons et al. (2001) developed a sequential inversion scheme of seismic traveltime and gravity data for a 3-D velocity structure, and applied it to the Seattle basin of Washington state, USA.

Therefore, we have to simultaneously or sequentially use various kinds of datasets for modeling the 3-D velocity structure of an urban basin. It is also necessary to verify a resultant model by seismic waveform studies, since this modeling is carried out mainly for strong ground motion prediction (e.g., Sato et al., 1999; Magistrale et al., 2000). We can calibrate velocity structure models by comparison of observed and synthetic dominant periods of spectral ratios and time history waveforms (e.g., Suzuki et al., 2005). Based on these experiences, we propose a standard modeling procedure in Japan, because extensive geophysical experiments and geological investigations have been carried out and velocity structure models are being constructed all over Japan. We then apply it to TMA for constructing a reference 3-D velocity structure model.

2. Modeling procedure

In seismology, two kinds of basement (bedrock) are defined in a velocity structure model. 'Seismic basement (bedrock)' is usually assigned to the uppermost part of the crust, whose S-wave velocity (V_S) is around 3 km/s, while 'engineering bedrock' with a V_S of 400 to 700 m/s is located just below surface layers. Regions between seismic basement and engineering bedrock are greatly influence long-period ground motion, so our modeling procedure targets these parts of subsurface velocity structures. Models for the crustal velocity structures from the seismic basement to the Moho discontinuity and the velocity structures of subducting plates must also be included to simulate strong ground motions from subduction-zone earthquakes.

If there are various kinds of exploration datasets and observed seismograms in such basins as the Kanto basin, we propose the following standard procedure used for their velocity structures in common. The applicability of this standard procedure for TMA will be examined in the next sections.

Step 1: Assume an initial layered model consisting of seismic basement and sedimentary layers from comprehensive overview of geological information, borehole data, and exploration results.

Step 2: Assign P-wave velocities to the basement and layers based on the results of refraction and reflection surveys, and borehole logging. Assign S-wave velocities based on the results of borehole logging, microtremor surveys, spectral-ratio analyses of seismograms, and empirical relationships between P- and S-wave velocities.

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