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Future Earthquakes and Their Strong Ground Motions in the Tokyo Metropolitan Area

Kazuki Koketsu* and Hiroe Miyake

Earthquake Research Institute, University of Tokyo

Abstract

The Tokyo Metropolitan Area (TMA) is located close to the triple junction of the Pacific, Philippine Sea, and continental plates. Various earthquakes occur in this complex plate system. Those generated by active faults might be candidates for future earthquakes beneath TMA, but their occurrence probabilities are not high. A deeper part of the Philippine Sea slab is also located beneath TMA. This part can generate a large earthquake with a high probability, so a prediction of strong shaking has been carried out following the recipe for strong ground motions. The occurrence probability of a subduction-zone earthquake along the Sagami trough is low because the 1923 Kanto earthquake occurred only 80 years ago. The probabilities of earthquakes along the Nankai trough are high. In particular, the Tokai earthquake has a probability as high as 86%. The DaiDaiToku project has made models of the Philippine Sea slab shape and the Kanto basin structure, and a 250 m-mesh geomorphological site classification map, which will enhance the accuracy of strong ground motion prediction.

Key words: future earthquake, subduction-zone earthquake, strong ground motion, Tokyo Metropolitan Area

1. Tokyo metropolitan area

According to plate tectonics theory, the Japan islands belong to a continental plate extending to Eurasia, under which the Pacific and Philippine Sea plates are subducting at the Japan trench, Kurile trench, Nankai trough, and Sagami trough as shown in Fig. 1 by the Earthquake Research Committee (ERC; 1999). The rates of subduction of the Pacific and Philippine Sea plates are as small as about 8 and 4 cm/year, respectively, but long-term subduction can lead to large stresses being accumulated between the oceanic and continental plates. A subduction-zone earthquake occurs when this stress is released.

This kind of plate motion is also effective even at inland parts of the Japan islands that are distant from the plate boundaries in the ocean. Because the Pacific and Philippine Sea plates push the continental plate westward and north-westward, respectively, and the continental plate resists this movement, the compressional stress in the east-west or northwest-southeast direction is applied beneath the Japan islands. The strain due to this compressional stress also accumulates, and is released along a weak plane in the crust, which is actually an active fault, generating an earthquake. This active-fault earthquake is a typical metropolitan earthquake. The Kobe (Hyogo-ken Nanbu) earthquake, which caused the great Hanshin-Awaji earthquake disaster, belongs to the category of active-fault earthquakes.

Because the Tokyo Metropolitan Area (TMA) is in a region where the Pacific and Philippine Sea plates neighbor (Fig. 1), these plates and the continental plate meet each other in a complicated way under the ground. Accordingly, various subduction-zone earthquakes or metropolitan earthquakes can be generated, as shown in Fig. 2 by the Central Disaster Prevention Council (CDPC; 2004). Here, we consider their occurrence probabilities and shaking, based on the "National Seismic Hazard Maps for Japan" (ERC, 2005).

* e-mail: koketsu@eri.u-tokyo.ac.jp (1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan)

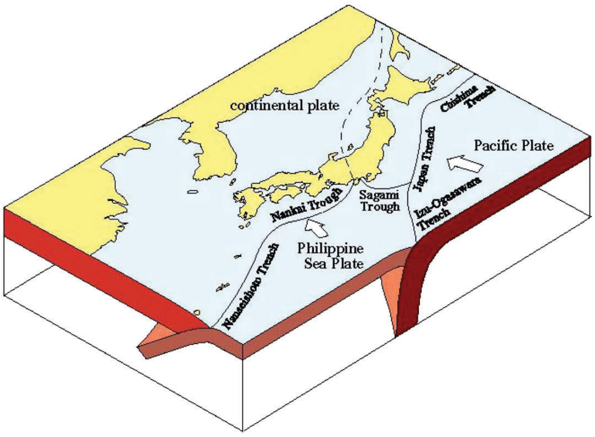

Fig. 1. Various plates around the Japan islands (ERC, 1998). The Pacific and Philippine Sea plates are subducting under a continental plate at the Japan and Kurile trenches, and Nankai and Sagami troughs.

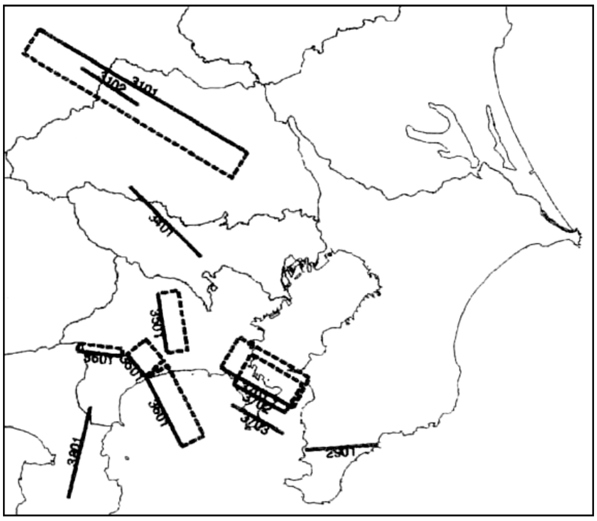

Fig. 3. Active faults in TMA (Group 1 in Fig. 2) (ERC, 2005).

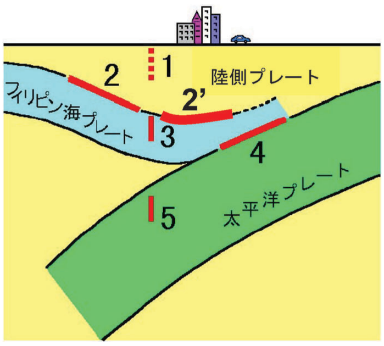

Fig. 2. Three plates in TMA (CDPC, 2004). The Pacific and Philippine Sea plates (太平洋・フィリピン海プレート) are subducting under the continental plate (陸側プレート).

Table 1. 30-year probabilities of active faults in TMA (ERC, 2005).

No.	30-year Probability
3101	nearly 0%
3102	0.43%
3401	1.3%
3501	nearly 0%
3601	4.2%
3701	0.0047%
3702	8.4%
3703	1.9%
3801	nearly 0%

2. Future metropolitan earthquakes

We first examine active-fault earthquakes as metropolitan earthquakes. Figure 3 shows active faults in TMA, which were chosen from among "98 major active fault zones" (ERC, 2005). Table 1 lists the 30-year probabilities of earthquake occurrence (probabilities that earthquakes will occur in the next 30 years) along these active faults. ERC (2005) defined a 30-year probability of 3% or larger to be high. High probabilities are further divided into three ranks: "fairly high" (3%〜6%), "high" (6%〜26%), and "very high" (26%〜). Because the active faults in TMA have 30-year probabilities smaller than 3%, except for Nos. 3601 and 3702 at ranks of "fairly high" and "high," they are not so significant for future earthquakes.

The Philippine Sea plate is subducting from the Sagami trough beneath TMA, generating earthquakes at a deeper part of its upper boundary and within its slab (earthquakes of Groups 2' and 3 in Fig. 2). These subduction-zone earthquakes should be metropolitan earthquakes because they occur at great depths directly beneath TMA. A committee of CDPC (2004) examined not only active-fault earthquakes but also plate-boundary earthquakes on the Philippine Sea plate.

As shown in Fig. 4, 19 fault planes were assumed on the plate boundary, and seven of them in northern Tokyo bay, Tama region, and southern Ibaraki prefecture were chosen because of the high potential for earthquake occurrence. In "General principles relating to countermeasures for earthquakes directly below the Tokyo Metropolitan Area" (CDPC, 2005),

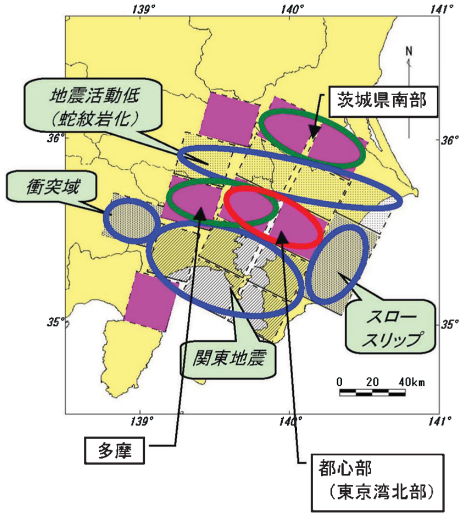

Fig. 4. Earthquake faults at the Philippine Sea plate (CDPC, 2004). The gray zones are omitted because of the Kanto earthquake (関東地震), slow slips (スロースリップ), collision zone (衝突域) and low seismicity (地震活動低). There remain three candidates in purple: northern Tokyo bay (東京湾北部), Tama region (多摩), and southern Ibaraki prefecture (茨城県南部).

countermeasure policies were prepared for a magnitude 7.3 earthquake from the two fault planes in northern Tokyo bay because the most severe damage was estimated for this earthquake.

ERC (2005) computed the 30-year probability for deep plate-boundary earthquakes on the Philippine Sea plate (Fig. 5). Adding the probabilities of earthquakes in the Philippine Sea plate (Fig. 6) and at the upper boundary of the Pacific plate (Fig. 7), ERC (2005) obtained a total 30-year probability as large as 72% for a future metropolitan earthquake in TMA.

3. Future subduction-zone earthquakes

The 1923 Kanto earthquake, which caused the great Kanto earthquake disaster, is a typical subduction-zone earthquake occurring around TMA. The fault plane of this earthquake is located at a shallow part of the Philippine Sea plate (Fig. 8). Because the 1703 Genroku earthquake occurred in the combined region of the fault plane and a neighboring area in the east, the recurrence interval of the earthquake is about 220 years. It is only 82 years since the Kanto earthquake, so ERC (2005) obtained a 30-year probability as small as 0.065%. However, the recurrence interval is not long, so the 50-year probability will reach 0.85%.

The part of the Philippine Sea plate along the Nankai trough is distant from TMA, but the 30-year probabilities of large plate-boundary earthquakes on it are very high. Previous studies assumed three source regions in this part as shown in Fig. 9. The earthquakes individually generated from the source regions are called the Tokai, Tonankai and Nankai earthquakes.

In history, these three earthquakes occurred not only individually but also simultaneously in various combinations. ERC (2005) computed the 30-year probabilities for all combinations (Table 2). As the source region of the Tokai earthquake has not ruptured for a long time, the 30-year probability of the Tokai earthquake only is as high as 18%, and the sum of the 30-year probabilities for all combinations including the Tokai earthquake reaches 86%. On the other hand, the probability that these source regions will never rupture is fairly high at 2.8%.

4. Strong ground motions in TMA

The best ways of predicting strong ground motions in TMA differ according to type of earthquake. For a shallow plate-boundary earthquake (*e.g.,* the Kanto, Tonankai and Nankai earthquakes), we know about strong ground motions during a previous event because of the short recurrence interval (100–200 years). We also know that a shallow plate-boundary earthquake repeatedly ruptures in a single pattern ("hypothesis of persistent asperities;" *e.g.,* Okada *et al.,* 2003). Therefore, a detailed investigation of strong ground motions from a past event should lead to a prediction of strong ground motions from a future plate-boundary earthquake.

Figure 10 shows the results of this kind of investigation for the 1923 Kanto earthquake (Moroi and Takemura, 2002). For example, it is important for the prediction of strong ground motions from a future Kanto earthquake that the intensities 6+ and 7 are distributed in the eastern parts of Tokyo and Saitama far from the source region.

Strong ground motions from previous events of some plate-boundary earthquakes are not well known, because their recurrence intervals might not be short or previous events might have occurred in prehistory of seismology. The northern Tokyo bay earthquake assumed by CDPC (2004), as well as the

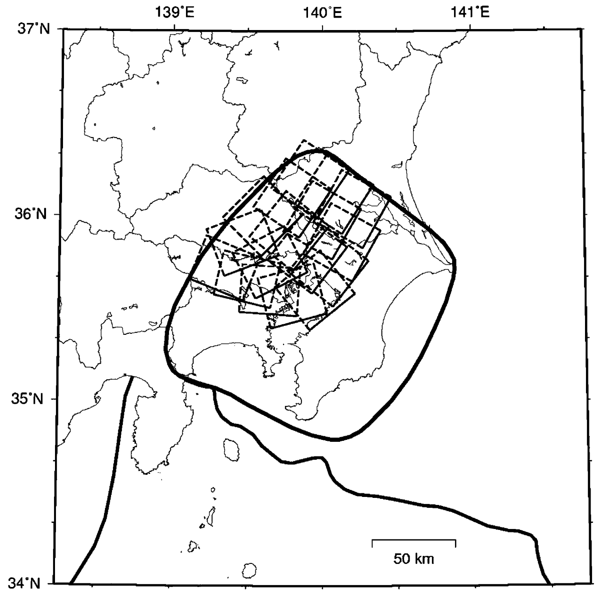

Fig. 5. Earthquake faults on the Philippine Sea plate (Group 2' in Fig. 2) (ERC, 2005).

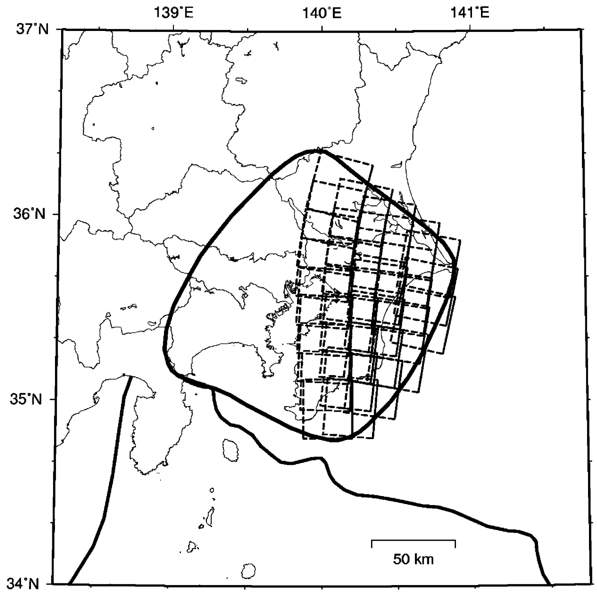

Fig. 7. Earthquake faults on the Pacific plate (Group 4 in Fig. 2) (ERC, 2005).

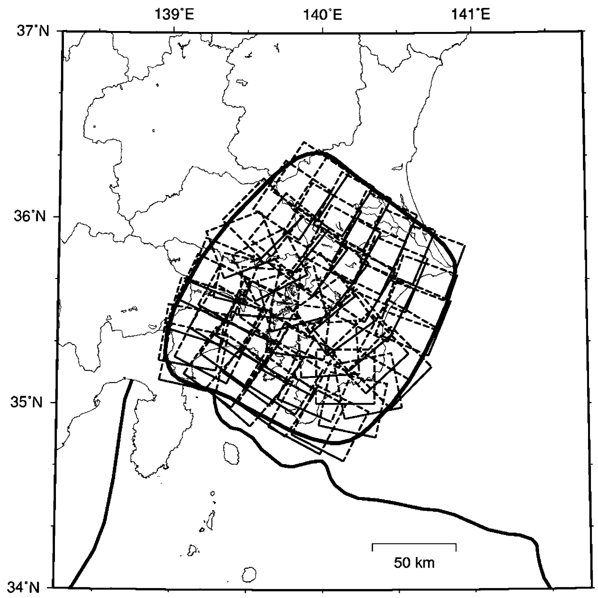

Fig. 6. Earthquake faults in the Philippine Sea plate (Group 3 in Fig. 2) (ERC, 2005).

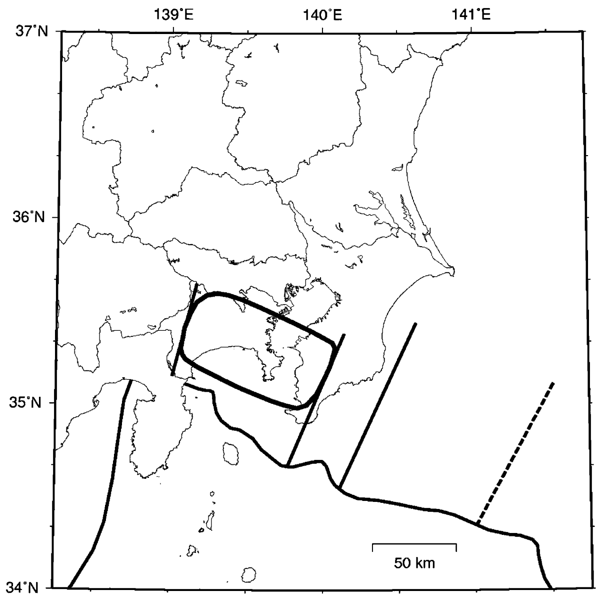

Fig. 8. Source regions along the Sagami trough (Group 2 in Fig. 2) (ERC, 2005).

Tokai earthquake, are such cases. Some seismologists insist that the 1855 Ansei Edo earthquake is an ancestor of this earthquake, but this has not yet been validated. Active-fault earthquakes are in a similar situation because their recurrence intervals are on the order of a few thousands years, and the hypothesis of persistent asperities has not been established for them.

To predict strong ground motions from these kinds of earthquakes, we use the recipe of Irikura and Miyake (2001), as written in Irikura (2006). Figure 11 shows the source model and the distribution of seismic intensities predicted for the northern Tokyo bay earthquake using the Irikura-Miyake recipe. The intensities of 6+ above the source model and along the northern coast of the Tokyo bay are due to

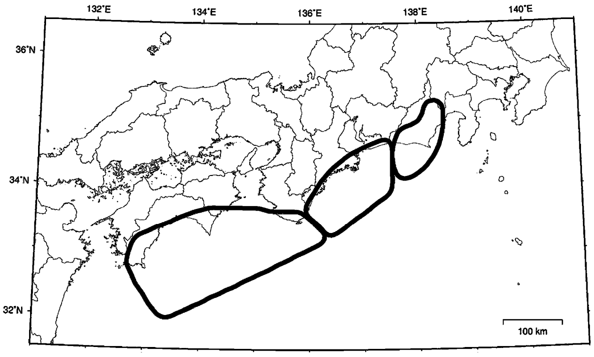

Fig. 9. Source regions of the three major earthquakes along the Nankai trough (ERC, 2005).

Table 2. 30-year (30年) and 50-year probabilities (50年確率) for combinations of the Nankai (南海), Tonankai (東南海地震) and hypothetical Tokai earthquakes (想定東海地震) (ERC, 2005).

No.	南海地震	東南海地震	想定東海地震	30年確率	50年確率
(1)	×	×	×	2.8%	0.046%
(2)	←→	×	×	2.6%	0.24%
(3)	×	←→	×	4.3%	0.43%
(4)	×	×	←→	18%	1.5%
(5)	←→	←→	×	2.0%	1.1%
(6)	←	→	×	2.0%	1.1%
(7)	←→	×	←→	16%	7.9%
(8)	×	←→	←→	13%	7.0%
(9)	×	←	→	13%	7.0%
(10)	←→	←→	←→	6.3%	18%
(11)	←	→	←→	6.3%	18%
(12)	←→	←	→	6.3%	18%
(13)	←	―	→	6.3%	18%
	合計			100%	100%

near-source effects and amplification by coastal sediments.

During the Tokachi-oki earthquake on September 26, 2003, long-period ground motions developed in the Yufutsu basin 250 km away from the source region, causing damage to oil storage tanks in the City of Tomakomai (*e.g.*, Koketsu *et al.*, 2005). This situation is similar to that of plate-boundary earthquakes along the Nankai trough and the Kanto basin. If a future event of the Tokai or Tonankai earthquake takes place, TMA in the Kanto basin will suffer from long-period ground motions. It is highly likely that they will affect high-rise buildings, oil storage tanks, and long suspension bridges in the Tokyo bay region.

The off Kii peninsula earthquake with a magnitude of 7.4 occurred on September 5, 2004 in the source region of the 1944 Tonankai earthquake. As shown in Fig. 12, long-period ground motions from this earthquake at periods of 7–10 s developed in TMA. This observation supports the above forecast.

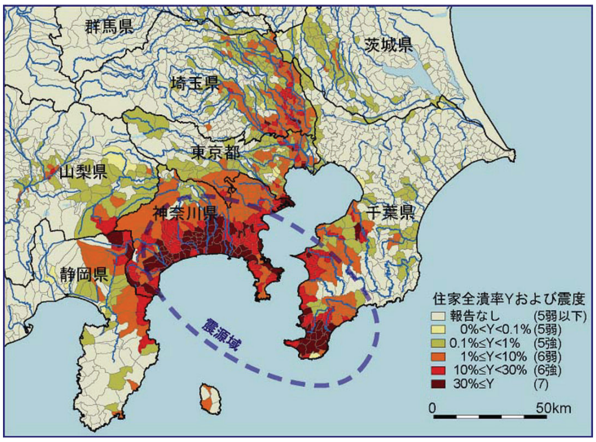

Fig. 10. Distribution of seismic intensities and the source region (震源域; blue ellipse) of the 1923 Kanto earthquake (Moroi and Takemura, 2002). The color tones indicate seismic intensities of 7, 6+ (6強), 6− (6弱), 5+ (5強), 5− (5弱), and lower than 5+ (5弱以下) in Tokyo (東京都), Saitama (埼玉県), and other prefectures around TMA.

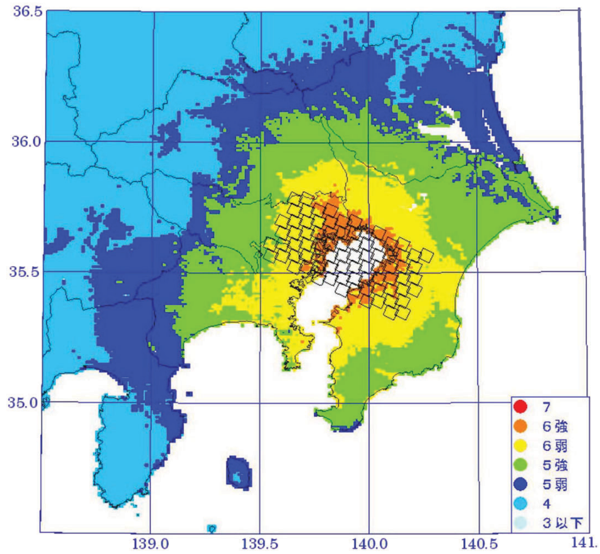

Fig. 11. Source model and seismic intensities predicted for the northern Tokyo bay earthquake using the Irikura-Miyake recipe (CDPC, 2004). The intensity ranks are indicated by the same Japanese names as those in Fig. 10.

5. Recent research

In the Special Project for Earthquake Disaster Mitigation in Urban Areas (the DaiDaiToku Project

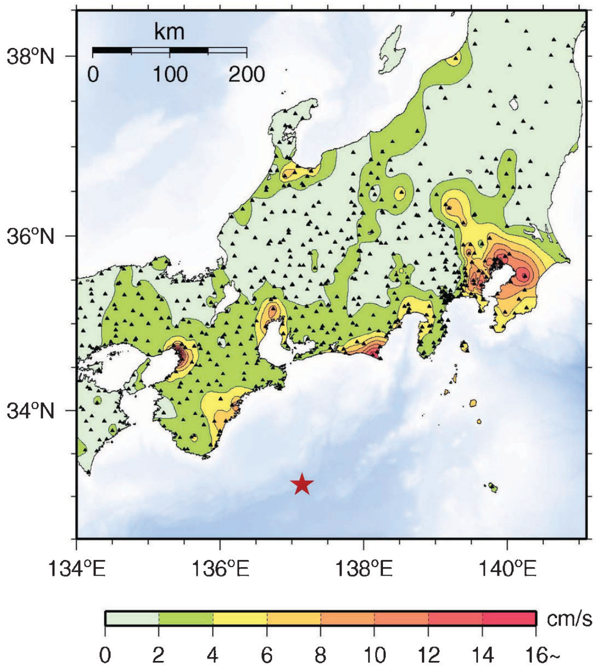

Fig. 12. Long-period ground motions at a period of 7 s from the 2004 off Kii peninsula earthquake (Miyake and Koketsu, 2005).

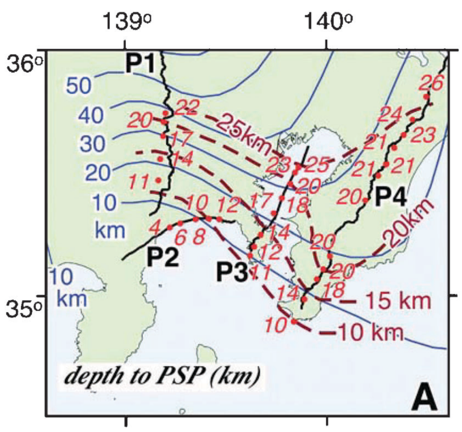

Fig. 13. Reflection survey lines and distribution of resultant depths to the Philippine Sea plate (Sato *et al.*, 2005). Blue lines denote the result of Ishida (1992).

in abbreviated Japanese), large-scale seismic reflection experiments were conducted along four survey lines, and the upper surface of the Philippine Sea plate was successfully imaged as illustrated in Fig. 13. This result indicates that the actual surface should generally be shallower than in previous models (*e.g.,* Ishida, 1992). For example, the depth just beneath Tokyo is estimated to be about 25 km in the

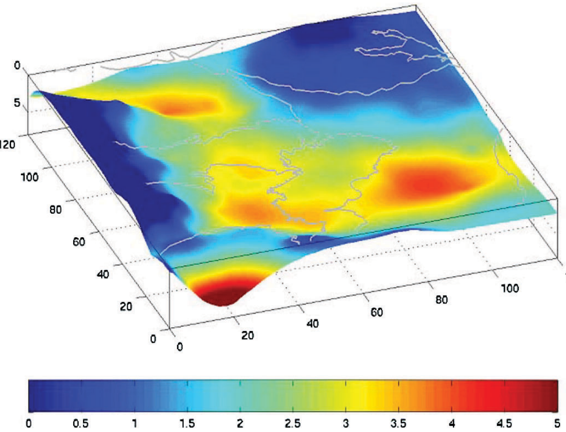

Fig. 14. Thickness in km of sediments in the new velocity structure model of the Kanto basin (Tanaka *et al.*, 2005).

survey result, while Ishida (1992) assumed it to be about 40 km. The source region of the northern Tokyo bay earthquake on the surface should also be shallower by 10 km. This implies that future ground motions could be stronger than those in Fig. 11.

The above reflection experiments also imaged sediments in the Kanto basin and basement surface over the crust. Using this information and data from other kinds of explorations and investigations at boreholes, we constructed a new velocity structure model with greater precision for the Kanto basin (Fig. 14). In a strong ground motion prediction based on the recipe of Irikura and Miyake (2001), long-period components are computed with this type of velocity structure model. Consequently, our model can improve the precision of the prediction.

In the strong ground motion prediction, local site effects are evaluated using engineering geomorphological classification maps. Although 1 km mesh maps were used in previous studies, we constructed 250 m mesh maps (Fig. 15). They can also help us to improve the precision of the prediction.

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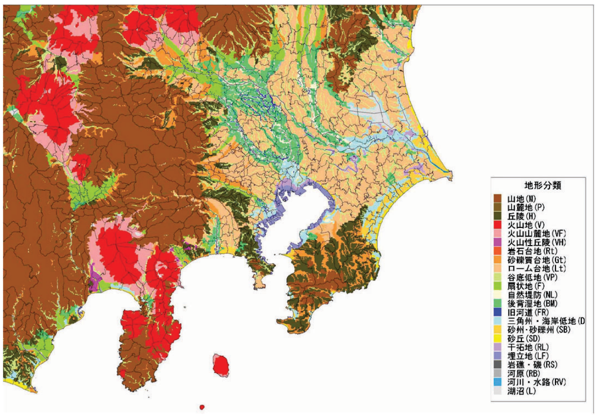

Fig. 15. 250 m mesh engineering geomorphological classification map of TMA (Wakamatsu and Matsuoka, 2005). The following 21 classes are used; 1) Mountain (M), 2) Mountain foot-slope (P), 3) Hill (H), 4) Volcano (V), 5) Volcanic foot-slope (VF), 6) Volcanic hill (VH), 7) Rocky terrace (Rt), 8) Gravelly terrace (Gt), 9) Terrace covered with volcanic ash soil (Lt), 10) Valley bottom lowland (VP), 11) Alluvial fan (F), 12) Natural levee (NL), 13) Back marsh (BM), 14) Abandoned river channel (FR), 15) Delta and coastal lowland (D), 16) Sand bar and gravel bar (SB), 17) Sand dune (SD), 18) Reclaimed land (RL), 19) Artificial fill (LF), 20) Reef and rocky coast (RS) and 21) Dry river bed (RB).

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