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# Three dimensional underground structure of Tokyo Metropolitan area

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ABSTRACT: A useful bit of information associated with the deep underground structure is essentials to estimate the input ground motion at the site due to the future earthquake. To obtain such information, observations of seismic waves generated from explosions (500 kg dynamite) at Yumenoshima, reclaimed land of Tokyo, were carried out twice every year at various temporary stations in Tokyo Metropolitan area from 1975 to 1988. In total, 27 explosions were fired at Yumenoshima. Analyzing the data thus obtained, the time term map of Tokyo Metropolitan area which is equivalent to the three dimensional depth contour map down to the pre-Tertiary base rock was deduced. The time term times 2.3 km/s gives us approximately the thicknesses of sedimentary layers down to the base rock. A good agreement was found between the depths obtained from the deep bore hole data and the ones estimated from the time term data.

## 1 INTRODUCTION

A huge development project is now going on along the coast of Tokyo Bay. Tokyo Metropolitan area, which includes the bay region, is overlaid by thick Quaternary and Tertiary deposits. Thus the long period ground motion, mainly of surface waves, will be excited not only due to the near earthquakes but also far events. Fig. 1 shows an example of the strong ground motion recorded at Tokyo station of Japan Meteorological Agency (JMA). Natural periods of horizontal and vertical components of JMA *strong motion seismograph are 6 and 5 s respectively.* The magnification of seismograph is 1. So, the seismograph records the ground displacement at the periods shorter than the natural period. The event was originated from off the east coast of Izu Peninsula about 100 km south-west of Tokyo. The origin time was June 29, 1980. The magnitude Ms of the earthquake was 6.7 and the felt intensity at Tokyo was 4 in JMA intensity scale. Still, the maximum amplitude recorded was 2.1

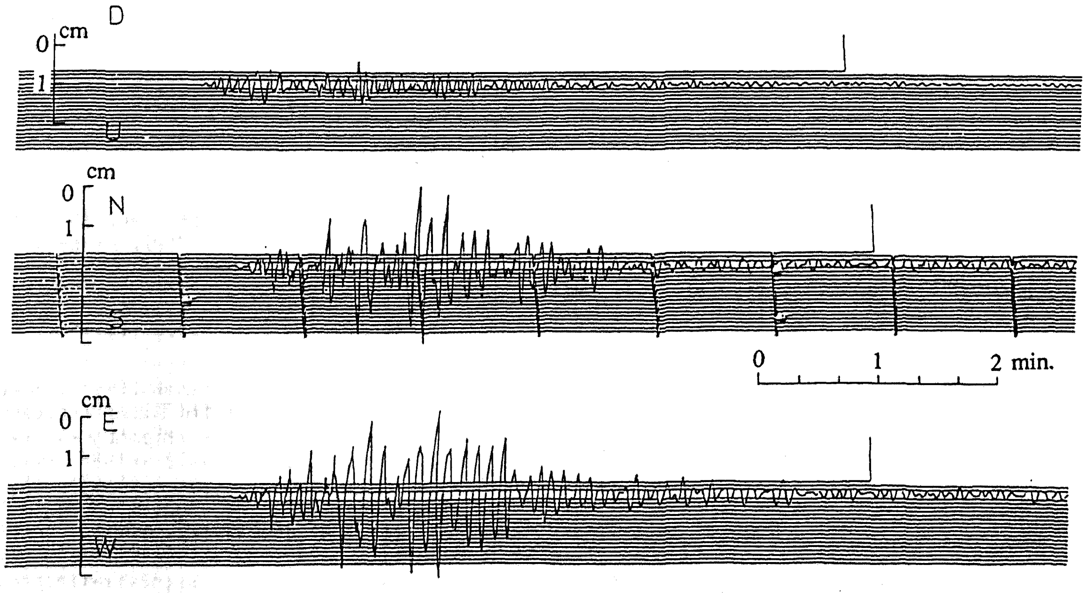


Fig. 1 Sample strong motion record obtained at JMA Tokyo station. Epicenter:Off the east coast of Izu Peninsula. Magnitude:Ms=6.7. Epicentral distance: Δ=98 km.

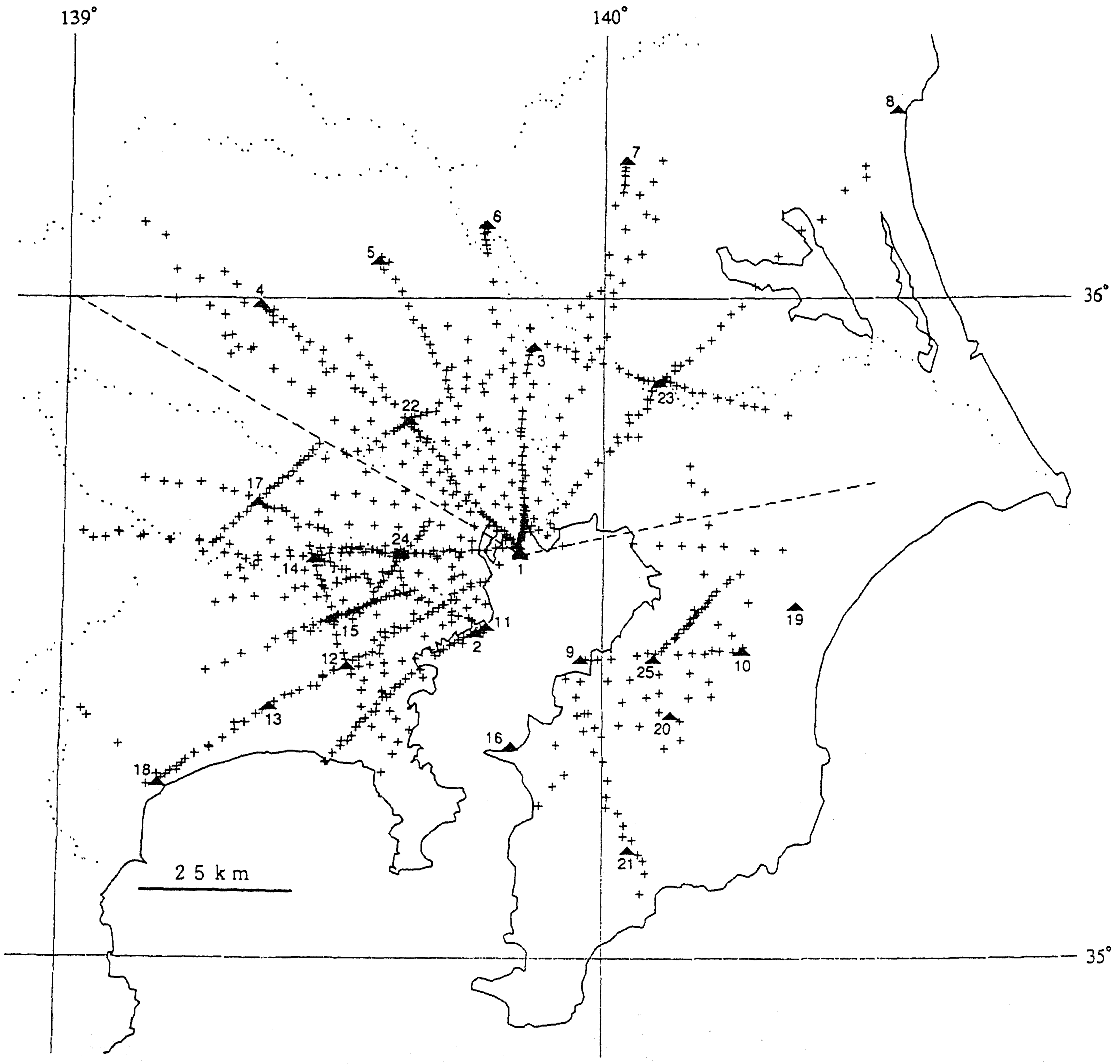


Fig.2 Distribution of shot and observation points.

cm in EW-component and 2 cm in NS-component. Seeing the figure one will notice that the long period strong ground motion lasted more than 2 minutes. Unfortunately, the seismicity in Tokyo Metropolitan area is higher than that of other Japanese territory. Especially 1923 Kanto Earthquake brought us the worst damage to the area ever experienced in Japanese history. The earthquake shown in Fig. 1 occurred very close to the focal region of 1923 Kanto Earthquake. Thus, in this region, a careful aseismatic designing of structures is indispensable especially to those having long natural periods such as huge oil tanks, high rise buildings and so on. The damping factor of such structures is very low. So the duration of ground shaking will be very important information to be clarified. To estimate the contribution of the long period ground motion, it is necessary to obtain the data associated with the three dimensional deep underground structure down to the pre-Tertiary hard rock. For the purpose, the series of seismic refraction surveys were conducted to clarify the three dimensional underground structure in this region. In the following, we will discuss the analysis of the data thus obtained.

## 2 DATA AND ANALYSIS

Observations of seismic waves generated from explosions at Yumenoshima, reclaimed land of Tokyo, were carried out twice every year at various temporary stations in Tokyo Metropolitan area from 1975 to 1988 (Shima et al., 1976a, 1976b,, 1978a, 1978b, 1981). The charge size and the shot depth were 500 kg dynamite and 100 m respectively. 27 such explosions were fired at Yumenoshima. Fig. 2 shows the distribution of shot (▲) and observation points (+). Yumenoshima shot points located in the north coast of Tokyo bay is shown as "1" in the center of the figure. To obtain the true velocity of the base rock, the reverse shot is essential. Other numerals

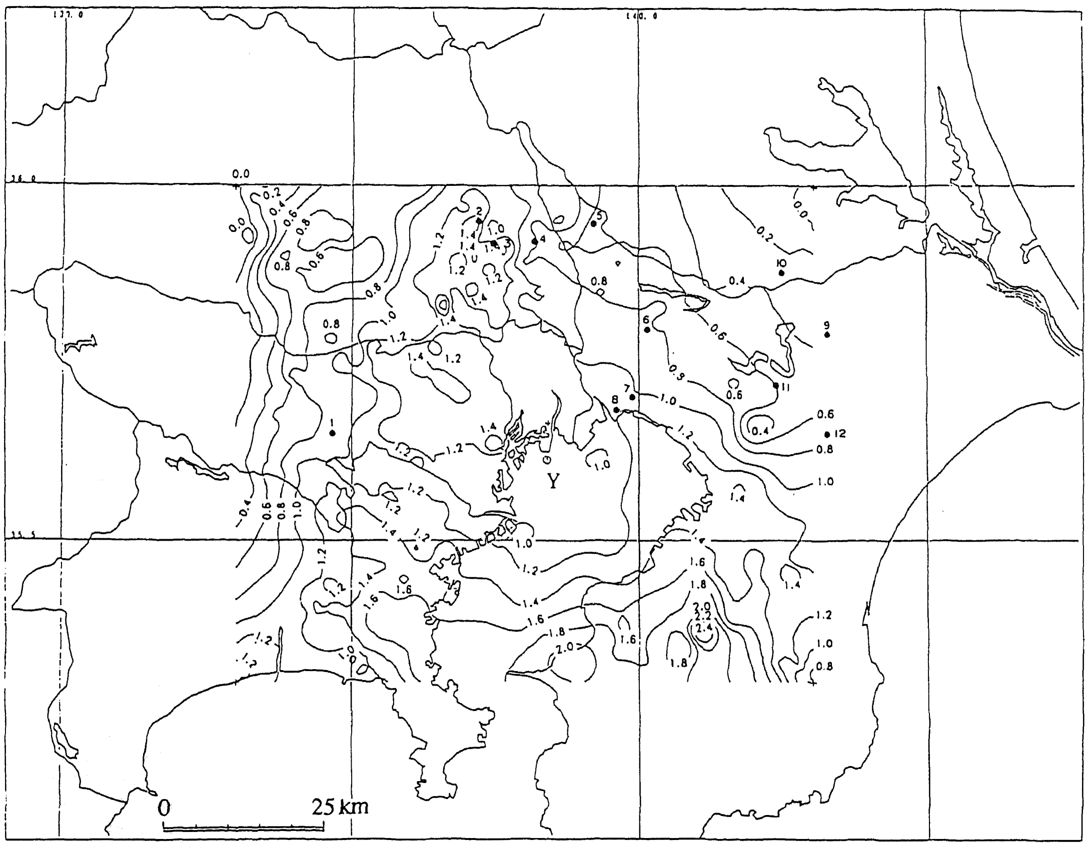


Fig.3 Time term map of Tokyo Metropolitan area.

shown in the figure are reverse shot points we observed for the purpose during the abovementioned period. If we denote the time terms of ith shot and jth observation points be Ai and Bj, the travel time T of the seismic wave at Bj from the shot point Ai can be written in the form

$$T = Ai + Bj + X/V,$$

where X and V are the distance between shot and observation points and the seismic wave velocity of the base rock. Unknown variables are Ai, Bj and V. So if we have N shot and M observation points, the number of unknown variables will be N + M + 1. Thus, if we have more than N + M + 1 observation data, we can solve all unknown variables. This technique is called 'the time term method'. Through the preliminary analysis of travel time data, it was known that the base rock P-wave velocity in northern part of the studied area was faster than that of the southern part. So, we divided the area into northern and southern parts by drawing two straight lines from Yumenoshima shot point. Then we applied the time time method to both parts and determined the velocities of base rocks separately. Changing the directions of straight lines little by little so that we could determine the stable velocities. Dashed lines shown in Fig. 2 show the boundary of velocity change thus obtained. And, P-wave velocities of northern and southern parts of the base rock were determined to be 5.6 and 5.4 km/s respectively. Yajima (1981) considered the boundary between Sanbagawa crystalline schists and Chichibu belt in this area through his study of petrological characteristics and geological structure of the pre-Tertiary basement of Kanto plain. Incidentally, the boundary we obtained agrees well with that of Yajima. For simplicity, we determined the time terms at observation points by fixing the time term at Yumenoshima and using the velocities of base rocks mentioned before. Now we will try to construct the contour map of equi-time term. For the purpose we utilized data within the region surrounded by longitude lines of 139° 18' and 140° 18' E, and latitude lines 35° 18' and 36° . We converted the irregularly distributed data to grid data following Pelto (1968) and Shiono (1982). Let the coordinate of grid point where we wish to obtain the time term be (Xi,Yj). Then we compute the distance Hr between grid point and observation point (Xr,Yr). By means of the weighted least square method, we computed the coefficients of quadratic function

$$f(X,Y)=a_{00}+a_{10}X+a_{01}Y+a_{20}X^2+a_{02}Y^2+a_{11}XY.$$

The weight $Wr=1/Hr^4$ was used in the computation. The time term value Zij at the grid point is equal to $a_{00}$. For the computation, data of ten observation points within 20 km from the grid point were used. The eqi-time term map was thus constructed and shown in Fig. 3. The time term times 2.3 km/s gives us the approximate depth down to the base rock.

From the figure, we can see that the depth down to the base rock well exceeds 3 km at the places in the NW of Yumenoshima shot point and Yokohama. The depth to the base rock is deepest at the central part of Boso Peninsula.

## 3 COMPARISON OF TIME TERM MAP WITH OTHER DATA

Table 1 and Fig. 4 are the comparison of depths down to the base rock from the deep bore hole data (Yajima, 1981; Yamamizu et al., 1981) and the ones estimated from the time term map. Sites of deep bore holes are shown in Fig. 3 by common number given in Table 1 and Fig. 4. We found a good agreement between them. Though it is an approximate approach, the time term map can be used conveniently to estimate the general trend of the undulation of base rock.

Fig. 5 shows the short wavelength gravity anomaly map after Hagiwara (1967). It is said that the short wavelength gravity anomaly is associated with the undulation of the base rock. That is why we compared Fig. 3 and Fig. 5. The contour line of 1 s shown in Fig. 3 seems to coincide with the contour line of 1 mg shown in Fig. 5 in northern and western parts of the studied area. However, the discrepancy is found in southern part. From Fig. 3, we know that the depth to the base rock increases once then decreases gradually in the central part of Boso Peninsula. On the contrary, the depth to the base rock seems to decrease monotonically in Fig. 5 from the center of Boso Peninsula to the south. Namely, the deepest sites of the surface layer from both figures do not coincide.

While, Kato (1984) carried out the multi-channel seismic reflection survey in Tokyo Bay. In the general trend his result was favorable to ours and negative to Hagiwaras.

Table 1. Depth of pre-Tertiary baserock in Kanto Plain.

| No. | Name of Bore Hole | Depth of Base Rock (m) | Time Term (s) | Estimated-Depth (m) |
|---|---|---|---|---|
| 1 | Fuchu | 2,024 | 0.9 | 2,100 |
| 2 | Kasukabe | 3,072 | 1.4 | 3,200 |
| 3 | Iwatuki | 2,897 | 1.2 | 2,800 |
| 4 | Matsubuse | 1,600 | 0.8 | 1,800 |
| 5 | Noda | 1,037 | 0.6 | 1,400 |
| 6 | Shimofusa | 1,520 ? | 0.8 | 1,800 |
| 7 | Funabashi A | 2,139 | 1.1 | 2,500 |
| 8 | Funabashi B | 2,071 | 1.1 | 2,500 |
| 9 | Narita | 1,018* | 0.4 | 900 |
| 10 | Shintone | 813 | 0.3 | 700 |
| 11 | Sakura | 1,510 | 0.6 | 1,400 |
| 12 | Yachimata | 1,989 | 0.7 | 1,600 |

* Suspicious

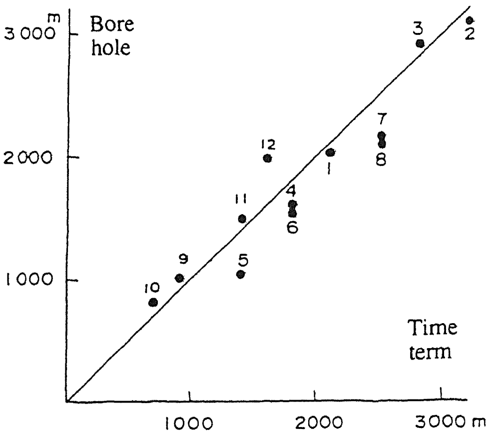


Fig.4 A comparison between the depths obtained from the deep bore hole data and depths estimated from time term.

## 4 DISCUSSION

From Fig. 3 we can draw an approximate cross section along any desired profile.However, this is not always convenient. We know that there are two surface layers above the base rock. Thus, time term utilized in Fig. 3 is the sum of contributions of two layers. So, if we could separate each contribution from the time term, we could obtain a better cross section. To do this, we tried to use the phases delayed due to multiple reflections in the surface layers. Fig. 6 shows schematically the ray paths of the late phases found in the sample seismogram. In the figure, it was shown that the once reflected wave P1 in the second layer arrive right after the first arrival. Let travel time of first arrival be Tp and that of late phase P1 be Tp1, then

$$Tp1 - Tp = 2Z_2\cos(\alpha)/V_2 ,$$

where $Z_2$ is the thickness of the second layer, $\alpha(=\sin^{-1}(V_2/V_3))$ is the critical angle, $V_2, V_3$ are the velocities in second layer and base rock. From above equation we may solve $Z_2$. But this is not always the case. In some cases, the later phase P2 once reflected in the 1st layer may arrive earlier than P1. It depends on the thicknesses of two layers. So, it is necessary to calibrate the travel times of reflected phases where the underground structure is known. Fig. 7 shows an example of NE cross section from Yumenoshima shot point thus obtained.

## 5 CONCLUSION

From 1975 to 1988, the refraction surveys were carried out in Tokyo Metropolitan area to obtain the three dimensional underground structure down to the pre-Tertiary base rock. Such information is useful to estimate the input strong ground motion at the site due to the future earthquakes. Analyzing the numerous data we proposed the time term map of Tokyo Metropolitan area.

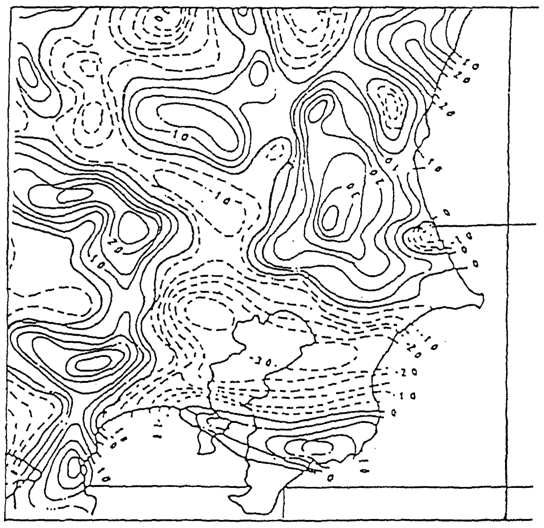
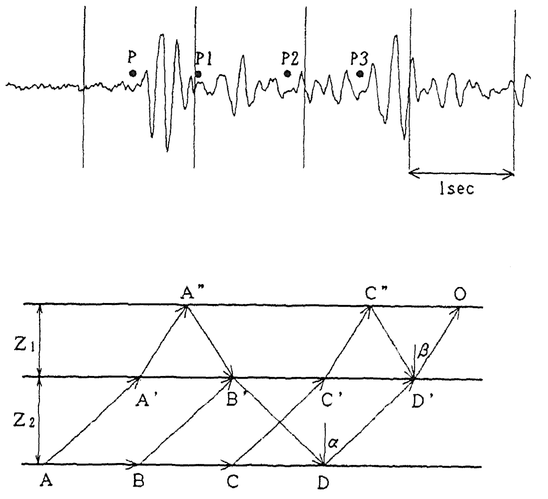


Fig.5 Gravity anomaly map (after Hagiwara).



P =ADD'O
P2=ACC'C"D'O
P1=ABB'DD'O
P3=AA'A"B'DD'O

Fig.6 Sample seismogram and the ray paths of reflected seismic waves.

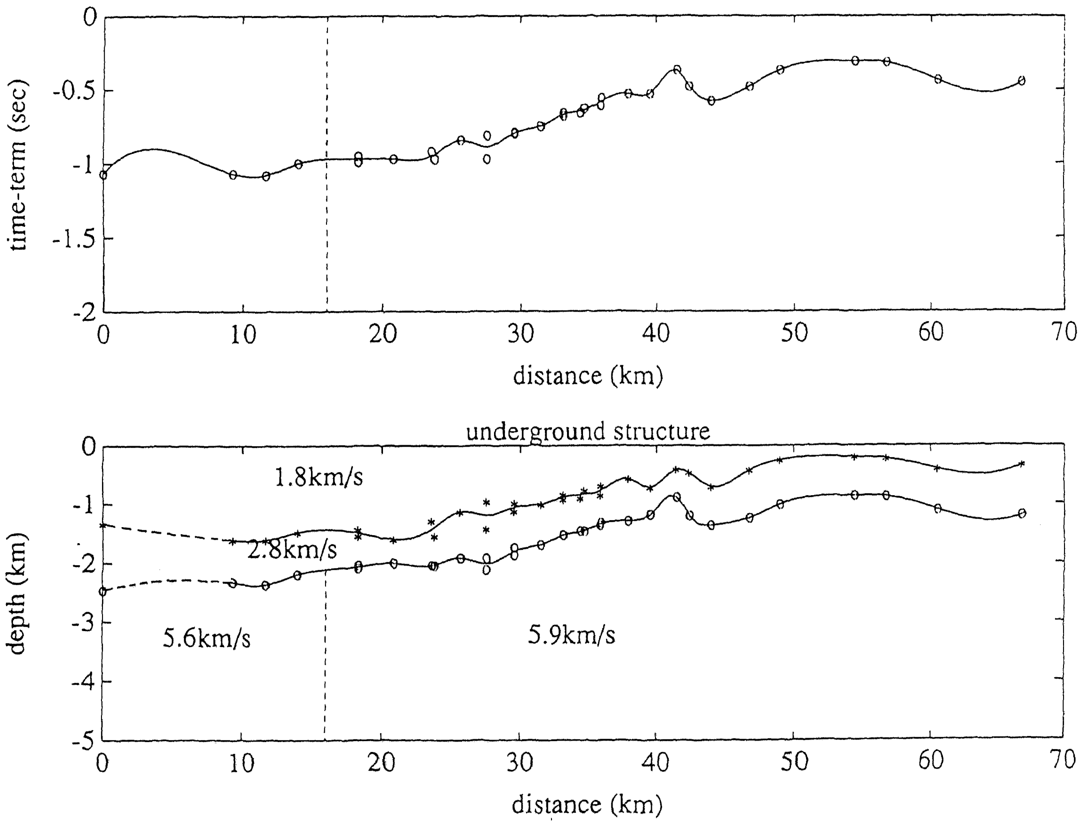


Fig.7 NE cross section from Yumenoshima shot point.

The time term times 2.3 km/s gives us the thickness of the sedimentary layers above the base rock.

Comparing the time term with the deep bore hole data, we found the good agreement between them. Thus, the time term map is useful to view the general trend of undulation of the base rock.

In general the tendency of undulation of base rock estimated from the short wavelength gravity anomaly map coincided with that of the time term map except in the southern part. But, the result of reflection survey carried out in Tokyo Bay is favorable to our result. Finally, we showed an example of the cross section along the profile NE from Yumenoshima shot point. To obtain the cross section we used the late phases delayed due to the reflection within the sedimentary layer.

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