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A STUDY ON CONSTRUCTING 3-D BASIN STRUCTURE MODEL CORRESPONDING TO INFORMATION AVAILABLE IN THE TARGET AREA

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SUMMARY

Practical procedure for constructing 3-D basin structure model is proposed for strong motion simulation. We produced smoothed 3-D boundary structure model using spline functions from information as much as it is available in target area. The model can be used for long period 3-D basin response of strong ground motion. The proposed modeling procedure was applied to the Osaka Basin, Japan. We modeled layered velocity structure of the Osaka Basin with 3 sedimentary layers and bedrock. Derived Osaka 3-D sedimentary basin model with velocity structure was verified through long period (T > 1sec.) waveform simulation using 3-D finite difference method. The results of the verification were fairly good. The proposed modeling procedure can be a useful tool to construct basin structure models for long period strong motion calculation at target sites with any accuracy that corresponds to quality and quantity of available information at the site.

INTRODUCTION

In this study, we propose a procedure for modeling 3-D basin structure and 1-D velocity structure of the basin. Modeling of the sedimentary basin structure is important issue not only for geological studies, but also for strong motion estimation. Without a good model of structure, any powerful calculation method can not be well applied real basin response. We adopted the procedure to the Osaka basin.

We employed a two-dimensional third-order B spline function after Koketsu [1] to make smooth structure model of bedrock surface. Using the function, it is possible to produce a model with arbitrary accuracy corresponding to information available in the target area. For well-studied areas like the Osaka basin, we can construct detailed structure model that not only matches the geological model but also is moderately smooth and useful for numerical calculations. Even for poorly explored area, it is possible to make simple and very smooth model from limited information.

The Osaka basin is surrounded by mountains that consist of mainly granite rocks. The depth of bedrock at deepest point is estimated to exceed 3 km. The necessity of surveying the deep basin structure was recognized as early as the 1960's in this area. After the 1995 Hyogoken-Nanbu (Kobe) Earthquake,

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numerous seismic exploration surveys have been conducted in this area (summarized by Iwata [2]). Now, the Osaka basin is one of the most heavily investigated sedimentary basins in the world. Kagawa [3] proposed four-layered (three sedimentary layers with bedrock) model as a general 1-D structure in the area. We used this basic information to produce our basin structure model.

The Osaka basin model was verified and additionally revised by waveform simulation using 3-D finite difference method (FDM). We compared the results with observed ground motions in period range T > 1 sec., and finally obtained a 3-D structure model of the Osaka basin that allows us to simulate strong motion records well in target period range.

GEOPHYSICAL EXPLORATIONS CONDUCTED IN THE OSAKA BASIN

The Osaka basin is a closed sedimentary basin which has an ellipsoidal shape with major and minor axes about 80 and 40 km, respectively. Fig. 1 shows the map of the studied area with geological information. The observed records in the central part of the basin have clear later phases of basin induced surface waves. To study characteristics of surface wave propagation in the Osaka basin and to apply the results to aseismic design, it is necessary to determine the deep basin structure.

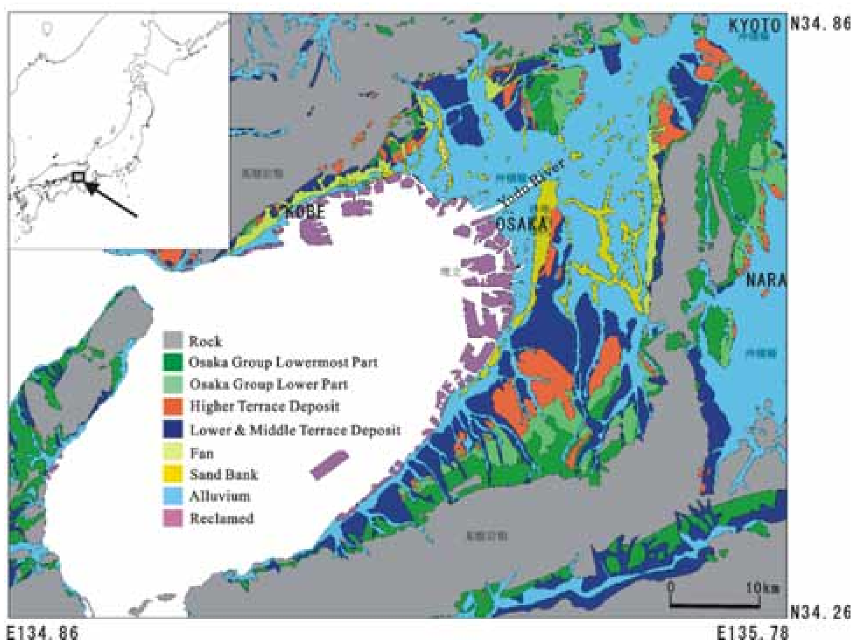

Fig. 1. Geology map of the study area. The Osaka basin is surrounded by mountains that consist of bedrock.

Numerous geophysical exploration surveys have been conducted in the Osaka basin. The first major survey (down-hole logging and basic seismic reflection) was conducted to study ground subsidence behavior in the 1960's (Ikebe [4]). Next big motivation arose from disaster in Mexico-city during the 1985 Michoacan earthquake, Mexico, because it was considered to be caused by the effect of sedimentary basin. Refraction surveys were conducted in 1988 (e.g. Kagawa [5]) and some additional seismic reflection surveys were made in the studied area (e.g. Iwasaki [6]). Gravity anomaly surveys were conducted to search for natural gas resources and several deep boreholes were drilled to obtain hot water for spas. Gravity anomaly data were analyzed already by previous studies (e.g. Nakagawa [7]). Microtremor array measurements focused on determining the S-wave velocity structure of the sediments were carried out (Kagawa [3]). Velocity structures were derived using phase velocities of Rayleigh waves. Four-layer model (V_P, V_S, density, thickness) derived by Kagawa [3] is used in this study.

After the 1995 Hyogoken-Nanbu (Kobe) Earthquake, many additional explorations were carried out. Seismic reflection surveys were mainly employed to obtain detailed and clear depth sections for detecting buried faults. Along the basin edge, bedrock depths were estimated from the peak period of the spectral ratio of horizontal over vertical components of microtremors (Wakamatsu [8]). We compiled these results into the unified 3-D Osaka basin structure.

MODELING OF THE BEDROCK SURFACE STRUCTURE

The bedrock structure is important for simulation of the seismic wave-field, because interface between sediments and bedrock forms strong velocity discontinuity. Also, bedrock depth in the model is an important key structure which is used to derive the depth of other sediment boundaries of the model. Here we show a method for modeling bedrock surface structure in first. We also demonstrate how detailed the model appears with increasing amount of available information.

We try to browse large-scale features of the bedrock surface structure. The left panel of Fig. 2 shows data points where bedrock depths were known from the investigation results before the 1995 Hyogoken-Nanbu (Kobe) Earthquake. Plus symbols around the basin indicate points where bedrock elevations are given as outcrop rocks. Closed circles are the points where bedrock depths were estimated by mainly geophysical exploration methods. These depths were directly read from field notes of deep borehole exploration, depth sections of seismic reflection and refraction surveys, the estimated model structure of microtremor array measurement, and gravity anomaly surveys.

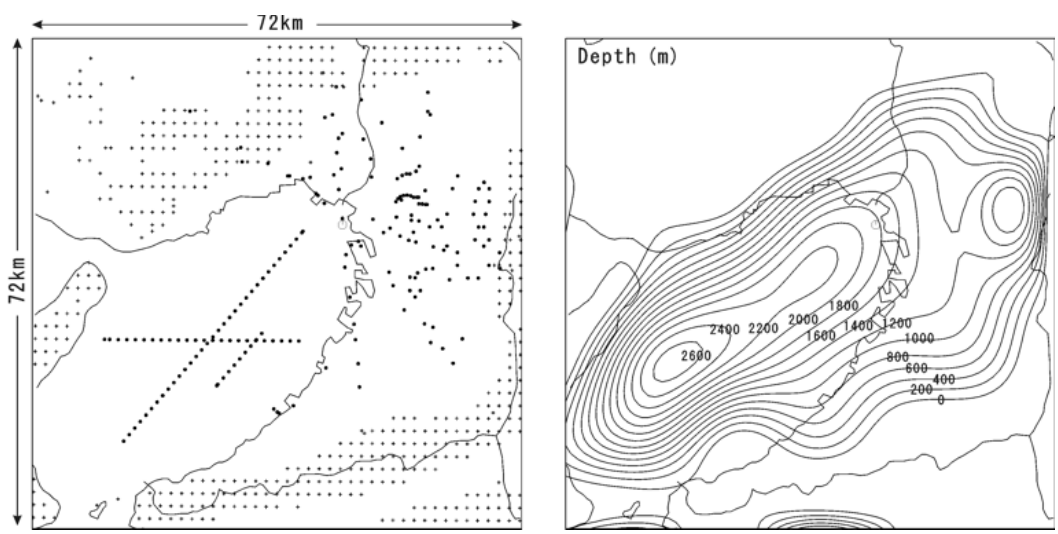

Fig. 2. Model of bedrock geometry of the Osaka basin derived from available information before the 1995 Hyogoken-Nanbu (Kobe) Earthquake. Left panel: data points where bedrock depth are given (pluses) or estimated (close circles). Right panel: contour map of the bedrock surface structure. The latitude and longitude of the reference point (X=45km, Y=44km) are N34.6603, E135.4011.

Because the given data points are spread widely and randomly, use of multi-spline functions is convenient to obtain a smooth model. Here, we used a two-dimensional third-order B spline function following Koketsu [1]. The target area is divided into several sub-areas shown in Fig. 3. For each sub-area, two-dimensional third-order B spline function is defined as:

$$z(x, y) = \sum_{i=I}^{I+3} \sum_{j=J}^{J+3} c_{i,j} B_{4+I-i}\left(\frac{x - x_I}{w_x}\right) \cdot B_{4+J-j}\left(\frac{y - y_J}{w_y}\right) \quad (1)$$

$$
\begin{aligned}
B_1(r) &= \frac{r^3}{6} \\
B_2(r) &= \frac{-3r^3 + 3r^2 + 3r + 1}{6} \\
B_3(r) &= \frac{3r^3 - 6r^2 + 4}{6} \\
B_4(r) &= \frac{-r^3 + 3r^2 - 3r + 1}{6}
\end{aligned} \tag{2}
$$

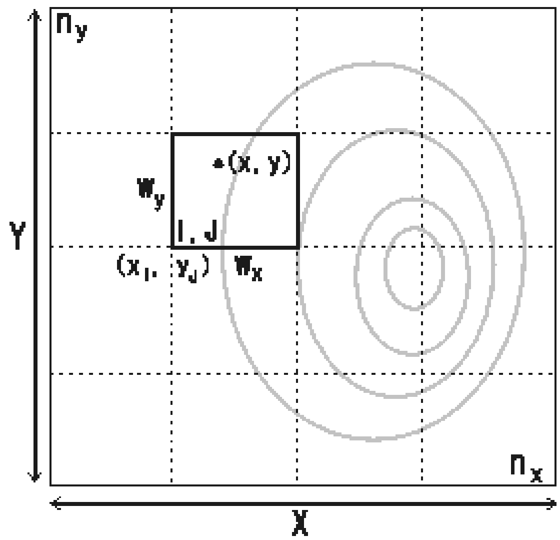

Fig. 3. Schematic diagram of sub-areas used in models with the multi-spline function.

Coefficients $c_{i,j}$ are estimated by using the least square method to minimize errors between data and model at the points, using a constraint that the neighboring spline functions are connected smoothly. In case that the target area is divided into M x N sub-areas, (M+3) x (N+3) coefficients are required in total. Once the coefficients are determined, we can calculate depths of the model at any point. Using the multi-spline functions, we can make a model with any degree of accuracy depending on the number of spline functions.

The right panel of Fig. 2 shows a resulting smoothed model (Kagawa [9]). Contours indicate the depth of bedrock. To construct the model, we use 6 x 6 sub-areas in this case. From available geological information close to the basin edges, we expect that the bedrock depth could change more rapidly, e. g., under Kobe City in northern part of the basin. Along the basin edges, the spline model of the bedrock structure is considered to be too smooth to fit the geological structure. To get higher order approximation it is necessary to increase number of observation points to have dense distance distribution of data points.

Fig. 4 shows a model constructed after the 1995 Hyogoken-Nanbu (Kobe) Earthquake (Miyakoshi [10]). Number of field exploration data increased remarkably. In this case, it is possible to divide the study area into a larger number of sub-areas, 8 x 8. The bedrock surface near thrust faults, e. g., basin edge, becomes steeper than before, but it seems still too smooth in the areas with dense distribution of data.

Next, we adopted a spline mapping technique, which is sometimes used for finite difference calculations. The aim of this technique is to make the spline model more closely approximate the data in regions of high density data and interesting change of structure. The concept is shown in Fig. 5. Shadow zone in the figure has higher density of the data points and smaller sub-areas to explain the steep change of the structure. Width of the shadow zone is doubled for each model sub-area. Then, the spline coefficients are obtained as usual. Lastly, the location of the target point is transferred into the new coordinate system and then the depth at the point is re-calculated.

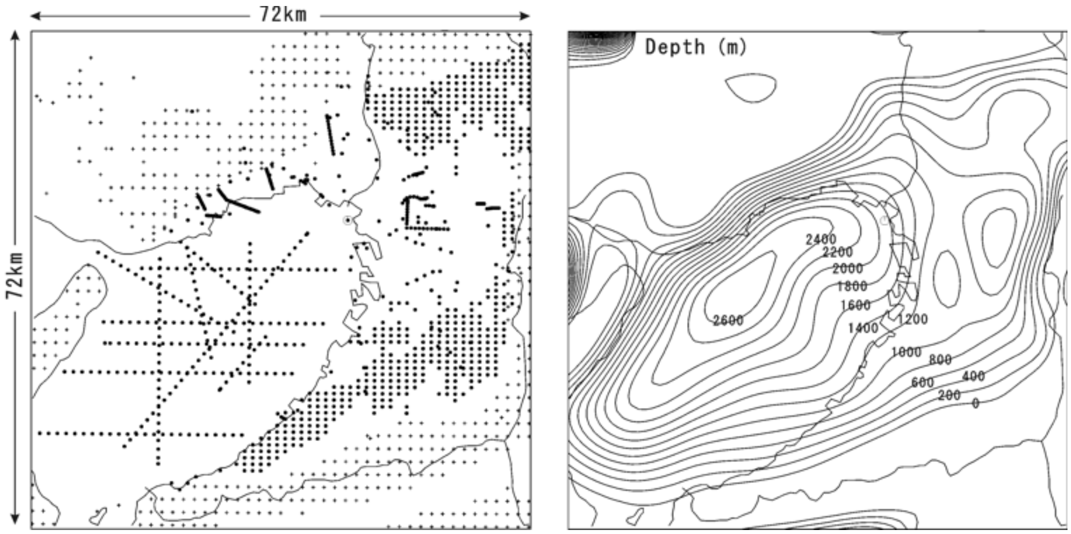

Fig. 4. Same as Fig. 2 but from additional data published after the 1995 Hyogoken-Nanbu (Kobe) Earthquake.

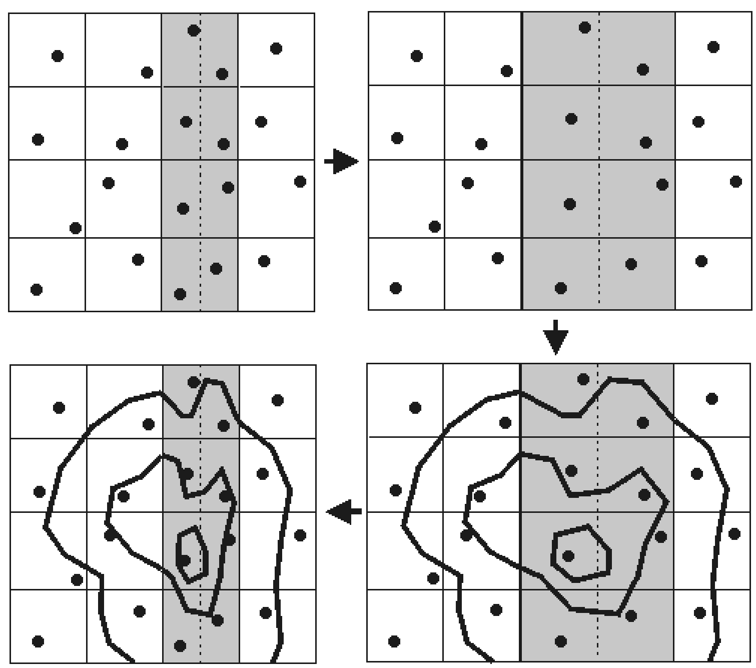

Fig. 5. Concept of the mapping technique in the case of non-uniform distribution of data points. Shadow zone is the region with high data density and structurally interesting. Arrows show steps of mapping procedure.

We adopted the new mapping technique for both N-S and E-W directions in regions bounded by the dash lines in Fig. 6 (Miyakoshi [11]). The total number of sub-areas is 10 x 10. Compared to the model in Fig. 4, the basin edge structure around Kobe City on Fig. 6 becomes steeper and similar to the results from geophysical investigations. The Uemachi underground ridge (beneath the sand bank in Fig. 1) is also well modeled. In this way, we obtained the initial model of the structure of bedrock depth in the Osaka basin. Below, the model is verified and refined to explain the observed records more accurately.

We consider that the procedure described above can be applicable to other sedimentary basin structures according to amount of available data. The proposed model can not explain structures with steep change such as overhangs, because we employ a spline function. However, the model is useful enough for earthquake ground motion simulations to explain behavior of basin induced surface waves. If more detailed structure is required, we recommend that the proposed spline function model is used as a first order approximation of the structure, and the simple model is modified in order to explain detailed structure. The modifications shall be performed sequentially including other information, e.g. geology or geography, and be verified based on waveform modeling.

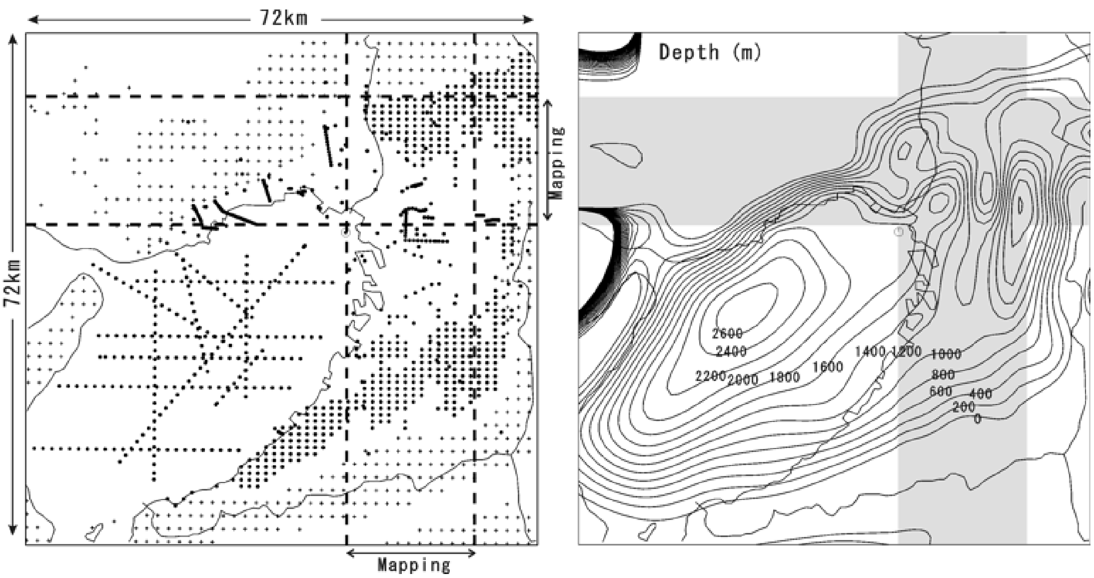

Fig. 6 Same as Fig. 4 but after applying the mapping technique with non-uniform sub-areas. Mapping area is bounded by dashed lines.

MODELING OF THE SEDIMENTARY STRUCTURE

We use geophysical parameters (P and S-velocities and density) of the basin after Kagawa [3] as follows. Almost all depth sections from seismic reflection survey have similar features in the basin. Fig. 7 shows an example of depth section from seismic reflection survey which was conducted along the Yodo River (Yamamoto [12]). The section crosses the Uemachi Fault that is slearly seen in the figure. Layering thickness changes drastically in three depth portions (Layer A, B, C). From the surface to a depth of around 200 m in the west side of the figure, the layering is less dense. Yamamoto [12] defined this portion as layer A whose P-wave velocity is 1.6 to 1.7 km/s. Below the layer A down to about 700 m, there are numerous reflection boundaries with P-velocity (V_P) of 1.8 to 1.9 km/s. This portion was defined as layer B. From about 700 to 1,500 m, again, there is a portion without dense layering with V_P = 2.0-2.8km/s. This layer was defined as Layer C. Yamamoto [12] defined the half-space, which consists of granite rock, as layer D with P-velocity higher than 3.0 km/s. Velocity of basement layer could not be well estimated from velocity analysis of seismic reflection survey. We fixed P-velocity of the rock half space as 5.4 km/s based on the results from a seismic refraction survey (Kagawa [5]). This four-layer structure corresponds well to other geophysical exploration results, e.g., gravity anomaly (Nakagawa [7]).

Based on the four-layer structure described above, other geophysical parameters including S-velocity were modeled (Kagawa [3]). They used Microtremor array measurements (Horike [13]; Matsushima [14]) for this purpose. By measuring microtremors using seismometer arrays, it is possible to evaluate propagation velocities of the surface waves that produce microtremor wave field. Because they use only the vertical component of the microtremors, the derived dispersion curves correspond to Rayleigh waves. For Rayleigh waves, the theoretical dispersion curve can be estimated from 1-D velocity model of the sedimentary structure under the site.

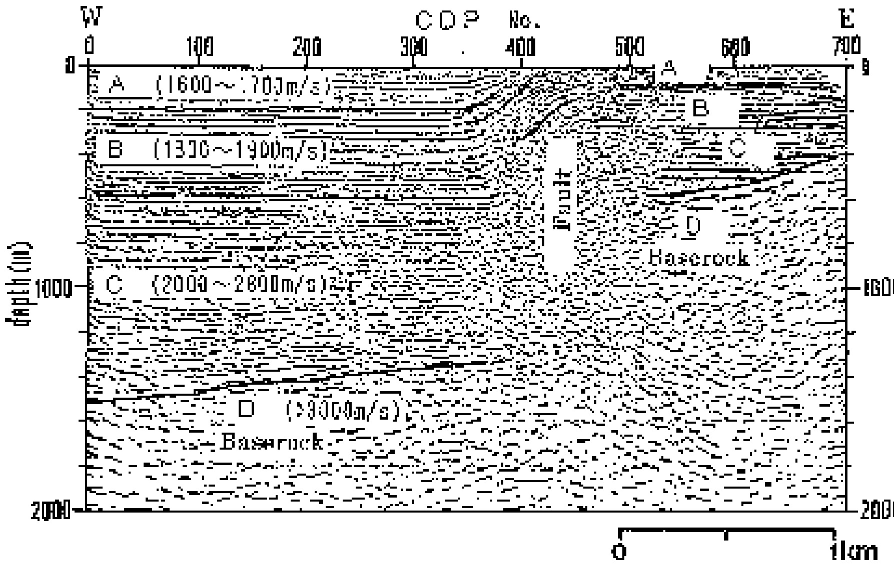

Fig. 7 Example of seismic reflection survey results in the Osaka basin. Figure shows a vertical cross-section along the Yodo River (from Yamamoto [12]).

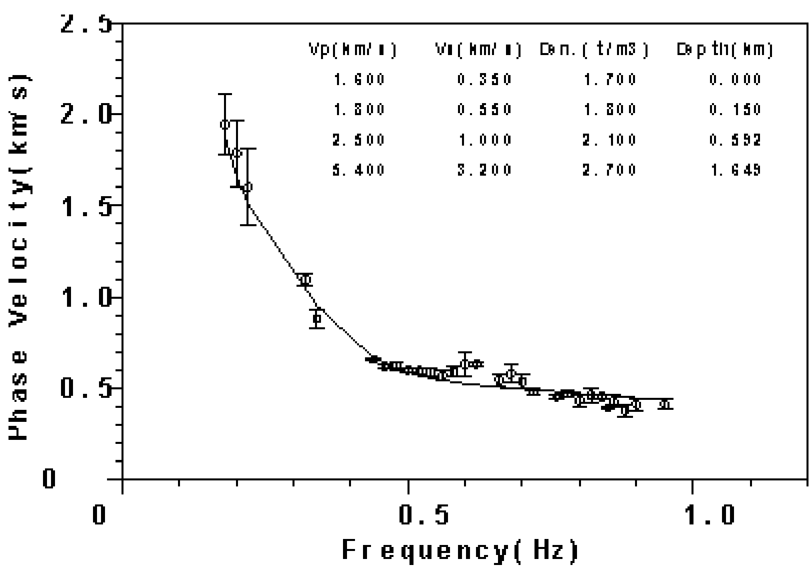

Fig. 8. Example of phase velocity dispersion derived from microtremor array observation at Naruo-hama site (points with error bars). Theoretical dispersion curve (line) of the fundamental mode of Rayleigh wave, calculated from the model structure indicated in the figure, is superimposed.

An example of the derived phase velocities and theoretical Rayleigh wave dispersion curve for the fundamental mode at the Naruo-Hama site are shown in Fig. 8. The layered 1-D structure shown in the figure is the result of inversion from observed phase velocities. The inversion for all sites was performed in two steps (Kagawa [3]). First, sites close to the seismic reflection profiles were used for analysis. In this step, physical parameters exclude S-velocities that are used for calculation of the theoretical phase velocities were derived from the results of neighboring explorations. Only the S-velocity for each layer was inverted from the observed phase velocities. Derived S-velocities for all layers were almost same for all sites. Then, they determined average S-velocities for the layers A, B and C. Next, the depths of layer boundaries were estimated from the phase velocities at the rest sites, after applying constrains on the physical parameters including S-velocities based on results of the previous step. Next, they obtained four-layered structure model that satisfies phase velocities derived from all microtremor observation sites. The model parameters are shown in Table 1. Around the Naruo-Hama site (Fig. 8), for example, fitting result of is good despite that there are no reflection profiles. This demonstrates that the model in Table 1 could be applied for arbitrary points in the Osaka basin.

Table 1. Four-layer structure model for the Osaka basin with three sediment layers and a rock half space (from Kagawa [3]).

Layer	Vp(km/s)	Vs(km/s)	ρ($\times 10^3$kg/m^3)
A	1.60	0.35	1.7
B	1.80	0.55	1.8
C	2.50	1.00	2.1
D(Baserock)	5.40	3.20	2.7

Lastly, they define proportional relationships between boundaries of the layers in Table 1. Fig. 9 shows the relationships between the depths of A/B and B/C boundaries (Z_{AB}, Z_{BC}) and the bedrock (Z_{base}), respectively from seismic reflection surveys and microtremor array measurements. Relations between the values are linear as follows.

$$Z_{ab} = 0.191 \times Z_{base} \quad (3)$$
$$Z_{bc} = 0.472 \times Z_{base} \quad (4)$$

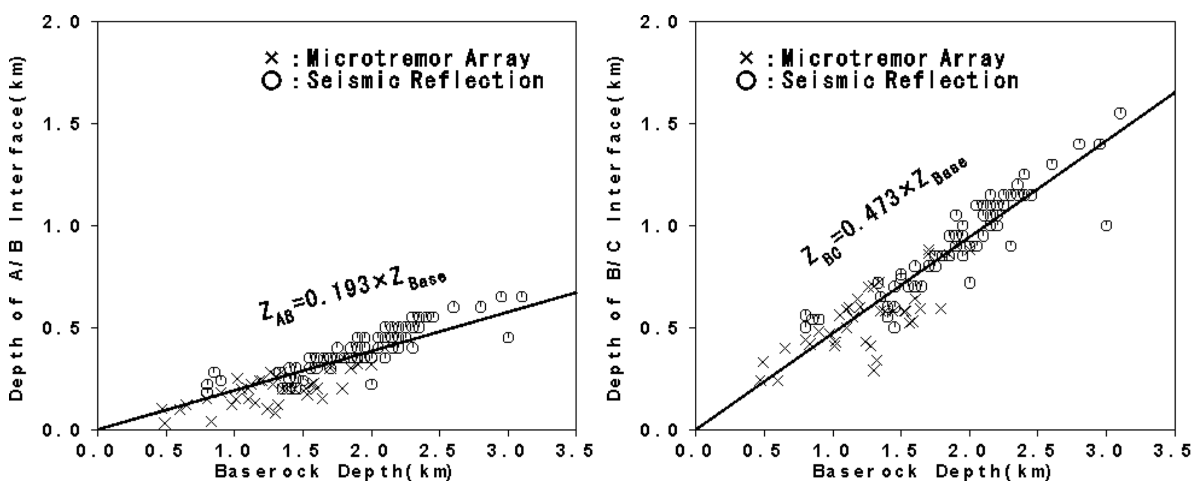

Fig. 9. Proportional relationship of A/B (left) and B/C (right) layer boundary depths and bedrock depth. Cross symbols indicate the values from microtremor array observations and circles are those from seismic reflection surveys. Coefficients of proportionality were derived as 0.193 and 0.473 respectively

We consider that these linear relationships between boundary depths and bedrock depth suggest a uniform tectonic activity in this region. The bedrock surface became deeper due to constant tectonic force, and sediments became thicker proportionally to the rate of tectonic processes. As a result, we can obtain depths of layered boundary at arbitrary points through bedrock depths derived from the spline function and the ratios (1) and (2). In case we need more detailed boundary structures, we can individually determine spline coefficients for each boundary from raw data of boundary depths.

The derived layered model shows good agreement with the geological model and deep borehole loggings down to the bedrock (Kobayashi [15]). From comparison with the layered model (Fig. 1) and geological data obtained from deep boreholes, it is shown that the A/B boundary of the layered model corresponds to the surface of the Ma8 marine clay layer. The age of Ma8 is estimated as 0.5 million years. The B/C boundary is considered to be a geological interface between the Lower Osaka Formation and the Lowest Osaka Formation (Ikebe [4]).

VERIFICATION AND FURTHER REFINMENT BSED ON WAVEFORM MODELING

We used the Osaka basin structure model (Fig. 6) to simulate seismic wave propagation. An earthquakes with magnitude M_J3.6 and focal depth of 14 km occurred at 1997.10.24 02:18 JST are selected as a target event. The epicenter of the event is indicated as a circle on the map in Fig. 10. Focal mechanism of the event was estimated by waveform fitting at stiff sites with horizontal layered model of crustal structure (Bouchon [15]). Using the focal mechanism, 3-D finite difference simulations (Graves [16]; Pitarka [17]) were conducted. The structure model was additionally refined to fit the ground motion waveforms observed at sites in the basin. In this process, we take special care to adjust the location of the basin edge, because the distances from the basin edge to the target sites have large effects on the shape of simulated waveforms. The shortest target period for the simulation is about one second.

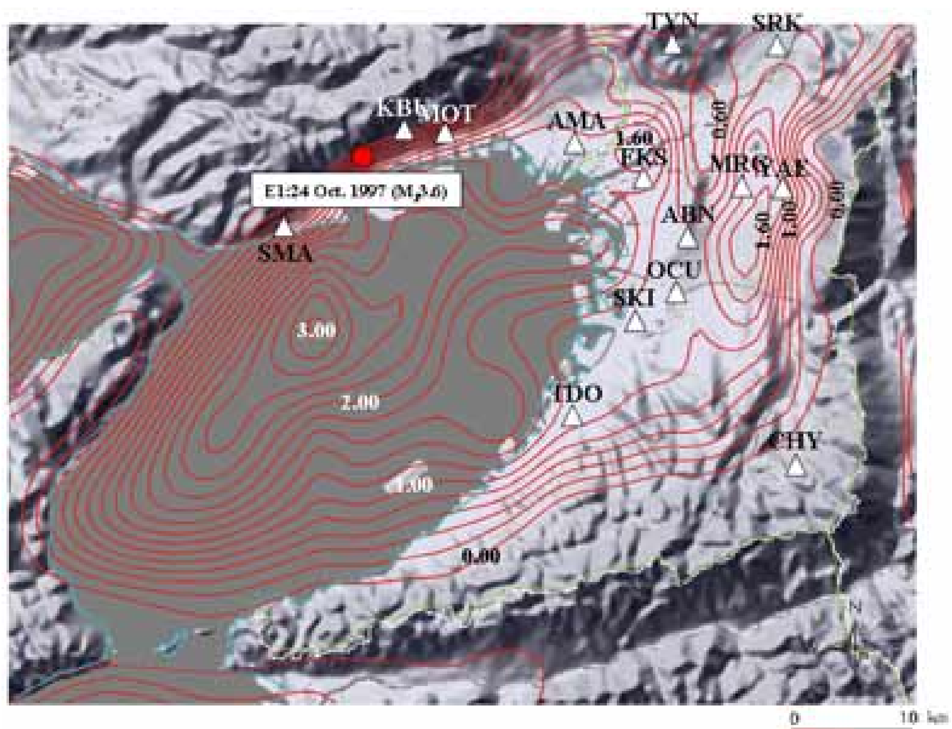

Fig. 10. Locations of sites (triangles) for the 3-D finite difference simulation and epcicenter of target event (circle).

After several trials, we derived a final multi-spline model for the Osaka basin. Our criteria to quit revision of the model are matching of arrival time and amplitude of main S wave portion, and generation of surface waves. The final model is shown in Fig. 11. Here we slightly expand the study area from 72km x 72km to 81km x 81km. The area was divided into 14 x 12 sub-areas. The model (bedrock depth) is shown in the right panel of Fig. 11 and Table 2. The model reproduces well-known geological structure such as the Uemachi underground ridge and steep basin edges. Fig. 12 shows an example of waveform matching. Traces plotted are velocity time histories of band-pass filtered from 0.1 to 1.0 Hz. Good agreement between synthesized waveforms (thick traces) and observed waveforms (thin traces) are obtained all over the basin.

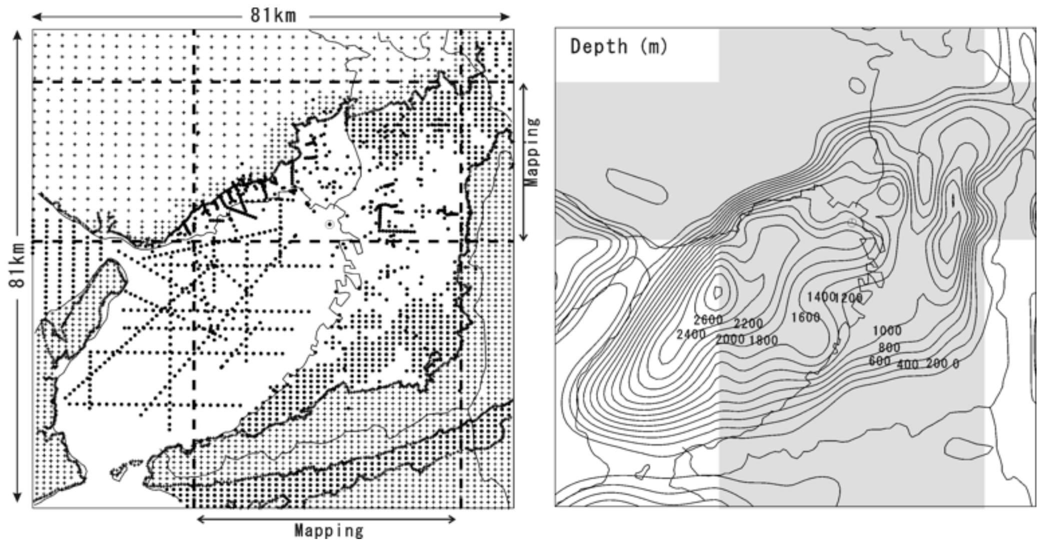

Fig. 11. Same as Fig. 6 but for newly developed model after adding recent exploration data and revising the model through comparisons between simulated traces (3-D finite difference method) and observed records. The latitude and longitude of the reference point (X=50km, Y=48km) are N34.6603, E135.4011.

Table 2. Coefficients of two-dimensional third-order B spline function for the model in Fig. 11.

		I																
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	1	2.005	2.077	1.226	1.965	0.548	0.210	-0.759	-0.104	-0.987	-0.365	-1.215	-0.393	-0.935	-1.119	-0.814	-0.730	-0.205
	2	-1.447	-0.188	1.585	-0.052	1.005	0.491	0.544	0.169	0.699	-0.138	0.000	-0.707	-0.491	-0.948	-1.281	-0.840	0.149
	3	0.790	-0.308	-1.379	-0.236	-0.808	-0.664	-0.569	-0.318	-0.515	0.083	0.021	0.190	0.302	0.331	0.777	-0.342	-0.767
	4	-1.479	-0.354	2.787	1.922	1.015	1.146	0.746	0.448	-0.024	-0.768	-0.953	-0.849	-1.163	-0.128	-1.541	1.259	-3.719
	5	1.967	-1.120	-0.400	4.197	0.678	1.952	1.502	1.837	2.757	1.510	1.652	0.851	1.310	-0.165	0.816	-3.170	15.046
	6	1.635	2.627	-1.923	1.006	4.740	2.633	2.834	1.292	0.825	0.739	0.427	1.336	0.670	1.549	-0.269	0.757	-2.852
	7	0.306	0.262	2.869	-1.870	2.244	1.217	2.471	2.535	2.568	2.609	2.717	0.777	1.150	2.899	-1.292	0.751	-4.261
J	8	1.665	1.965	-1.618	0.597	-0.882	3.006	2.059	2.199	0.637	1.841	0.760	1.491	0.382	1.475	2.558	-4.726	21.826
	9	1.437	-0.860	0.246	0.374	-0.911	-1.079	1.015	1.693	2.174	1.453	1.763	2.621	-0.958	3.427	-2.196	1.968	-7.710
	10	0.272	-0.177	-0.028	-0.232	0.253	-0.062	-1.926	-1.089	0.097	1.702	0.376	1.020	0.353	0.736	2.330	-3.271	12.052
	11	0.029	0.022	-0.112	0.334	-1.002	-0.530	0.377	-0.459	0.123	0.659	1.967	0.016	0.883	1.066	0.552	1.365	-9.662
	12	-0.180	-0.172	-0.008	-0.332	0.122	0.063	-0.773	-0.163	-0.230	-0.410	-0.703	0.599	0.196	0.694	1.196	-0.482	6.959
	13	-0.045	-0.010	-0.063	-0.043	-0.352	-0.440	0.234	-0.109	-0.918	0.345	0.693	-1.711	-0.377	-0.212	-0.403	0.660	-0.872
	14	-0.159	-0.137	-0.006	-0.125	0.071	0.111	-0.725	-0.420	0.694	-0.342	-2.214	1.732	-1.190	0.850	-1.699	2.460	-4.475
	15	-0.265	-0.514	0.002	-1.786	-1.730	-0.925	1.124	-0.940	-3.241	-2.750	11.907	-13.933	6.005	-8.131	2.537	-1.140	-10.244

The model itself is very compact that consists only of spline coefficients as shown in Table 2. It is an additional advantage of the modeling procedure. It makes model transformation and modification easier than the other model, e. g., a grid model. And the model can create the depth data at any point because it is a function. This is also an advantage against multi section model. However, the model is rather smoothed, so very steep structure change could not be represented. In the case the simulation target is concentrated into such area where the structure steeply changes and there are a lot of field investigation data, it is better to employ such raw field data.

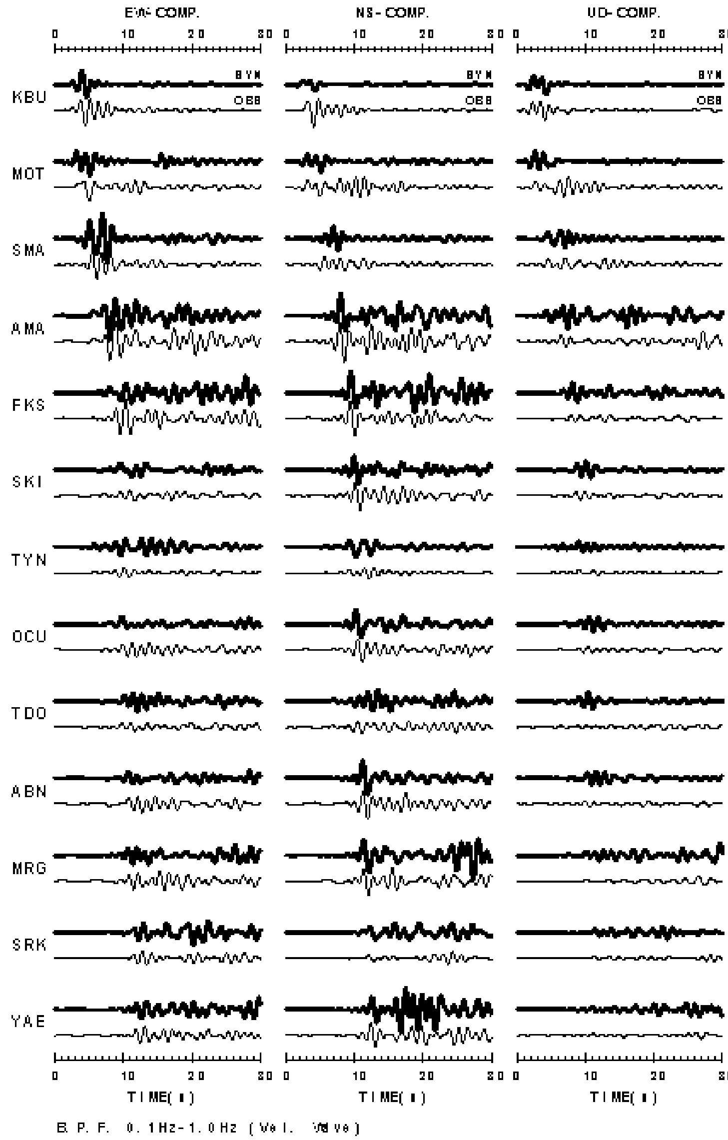

Fig. 12. Result of 3-D finite difference simulation for the earthquake occurred at northern edge of the Osaka Bay with M_J3.6. Thick and thin traces indicate synthesized and observed waveforms respectively.

CONCLUSIONS

We proposed a modeling procedure multiply using two-dimensional third-order B spline function. The procedure is able to construct an adequately smooth structure model that satisfies the amount of available information. The proposed procedure was applied to the Osaka basin structure. The resulting 3-D Osaka basin model was successfully verified through the 3-D simulation of seismic wave propagation. The results of simulations agree well with the observed waveforms in low frequency range (f < 1 Hz).

Using the proposed procedure, we can make intimate and precipitate structure model in case we have much information about target site. On the other hand, even in case that the target area does not have enough information about deep structure, we can obtain very brief and smooth model. For example, in case that there is no physical exploration data, we shall derive depth information at least from earthquake ground motion data if there is single observation station. We hope the procedure proposed can be a helpful tool to make basin structure model at any target area.

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