Modeling of the underground structure in the Osaka sedimentary basin based on geological interpretation of gravity anomalies and seismic profiles

INOUE Naoto¹ and NAKAGAWA Koichi²

¹ Department of Geophysics, Graduate school of Science, Kyoto University, Kitashirakawa-Oiwakecho, Sakyo-ku, Kyoto 606-8502, Japan
² Department of Geosciences, Faculty of Science, Osaka City University, Sugimoto 3-3-138, Sumiyoshi-ku, Osaka 558-8585, Japan

Abstract

The Osaka sedimentary basin includes Osaka Bay and the surrounding plains, Southwest Japan. The basin comprises the pre-Paleogene granitic basement rocks and thick Pliocene-Pleistocene deposits. After the 1995 Hyogo-ken Nambu earthquake, various organizations have carried out many geological and geophysical surveys involving geological field surveys, deep drillings, seismic reflection surveys, and gravity measurements. This paper presents a method of constructing a three-dimensional model of the underground structure, based on geological interpretation of gravity anomalies and seismic profiles in this basin.

Strong seismic reflectors in the seismic profiles were correlated to well known horizons in a deep borehole. Reflectors in seismic profiles were traced in and around Osaka Bay. The depths of the reflectors were sampled at 250 m-intervals as constraints in constructing the geological model. A linear relation was found between the depth of sediment layers and that of the basements.

The gravity measurements both on land and at sea bottom provide additional information for modeling. The Bouguer anomalies were separated into regional trends and residual anomalies. It is assumed that the regional trend is approximated by a polynomial, and the residual anomaly is proportional to the altitude of the basement rocks. The obtained relation between the residual anomaly and the altitude of the basement rocks enables us to estimate the altitude of the basement rocks from the Bouguer anomaly.

From these data sets, we constructed a four-layered model consisting of the basement rocks and three sedimentary layers, which satisfies constraints obtained from (1) seismic reflection surveys and (2) observed gravity anomalies. To verify the model, the gravity anomaly was calculated using density estimated from the P-wave velocity. The root-mean-square of the difference between observed and calculated gravity anomalies was 3.79 mgal.

Key words: Osaka sedimentary basin, seismic reflection survey, gravity analysis, regional gravity effect, three-dimensional model

1. Introduction

The Osaka sedimentary basin is located in Southwest Japan and includes Osaka Bay and the surrounding plains. In the Osaka Plain, which is the eastern part of this basin, many geological and geophysical surveys have been carried out. The stratigraphy of the formations under the plain was investigated from the results of some borehole data and geological field surveys. Nine boreholes, called OD borings, were drilled for the estimation of the land subsidence in the 1960s (Ikebe et al., 1970).

In order to investigate the underground structure, the seismic surveys were carried out around the active faults in the Osaka Plain, such as, the Arima-Takatsuki Tectonic line and the Uemachi fault (Yamamoto et al., 1992; Kawasaki et al., 1994). The relation between relief of the basement and the gravity anomaly was surveyed (Nakagawa et al., 1991). Marine seismic reflection surveys had earlier been conducted in Osaka Bay (Iwasaki et al., 1994).

After the 1995 Hyogo-ken Nambu earthquake, many organizations surveyed the subsurface geology and underground structure of Osaka Bay and Kobe. These additional surveys included gravity measurements at the bottom of the sea (Komazawa et al., 1996), a vast amount
2. Geological setting of Kinki district

The Osaka sedimentary basin is filled with thick Pliocene-Pleistocene deposits overlying the pre-Paleogene basement rocks (Fig. 2). The basin is surrounded by a complex fault system. The lower part of the Pliocene-Pleistocene deposits is fluvial and lacustrine sediments, including mainly silt, sand and gravel beds. The upper part consists of alternations of marine clay and fresh water sediments. The intercalated volcanic ash layers are used as marker beds for the stratigraphic study. The well-bedded marine clays in the upper part, referred to as Ma-1, Ma 0... Ma 13 (Itihara, 1961; Yoshikawa et al., 1987), are also useful marker beds.

3. Methodology

The geological model is constructed in two steps. In the first step, seismic profiles and gravity anomalies are interpreted, based on the geological information. Using the results from the first step, boundary surfaces of a three-dimensional model are computed in the second step, using a gridding algorithm.
3.1 Geological interpretation of geophysical data

3.1.1 Seismic Reflector

Several strong reflectors are selected as standard ones. The standard reflector must be strong enough to be traced in seismic profiles easily. The standard reflectors are correlated to sedimentary layers in a borehole drilled on or near the seismic survey line. The standard reflectors are traced from one profile to another, based on the intersecting points. It is easy to trace reflectors on time sections. However, if the depth section is used, there may be gaps between adjacent profiles due to some difference in velocity distribution for time-depth conversion. The depth of standard reflectors is sampled using the available seismic profiles.

3.1.2 Gravity Anomaly

Bouguer anomalies are separated into two components: regional anomalies due to a deep structure, and residual anomalies generated by a shallow structure. Residual anomalies are important for analysis of a sedimentary basin. Nakagawa et al. (1991) found a linear relationship between the altitude of the basement rocks and the residual anomalies. Inoue et al. (1998) attempted a polynomial approximation for the regional trend. Based on the previous studies, the following equation was proposed:

\[ g_{obs} = \sum_{i=1}^{m} \sum_{j=0}^{i} A_{ij} x^{i-j} y^{j} + C + \alpha z \]  \hspace{1cm} (1)

for the Bouguer anomaly, where \( g_{obs} \) is the observed Bouguer anomaly (mgal), \( m \) is the maximum order of the polynomial, \( x \) (km: positive toward east) and \( y \) (km: positive toward north) are distances from origin of the coordinate. In this study, the origin of the coordinate is at long. 135° 30′ E and lat. 34° 40′ N (in the same way as Nakagawa et al., 1991). \( z \) is the altitude of the basement rock (km), \( A_{ij} \), \( C \) and \( \alpha \) are constant. The first and second terms on the right-hand side represent the regional gravity anomalies. The last term indicates the residual anomalies. The least-sequence method is used to determine the coefficient of the equation (1).

Given a Bouguer anomaly, the altitude of the basement rock is estimated by

\[ z = \left( \frac{g_{obs} - \sum_{i=1}^{m} \sum_{j=0}^{i} A_{ij} x^{i-j} y^{j} + C}{\alpha} \right) \]  \hspace{1cm} (2)

The boundary surface between the basement rocks and
sedimentary layers can be determined, based on two types of data set: one from seismic profiles and the other from gravity anomalies.

3.2 Gridding of a boundary surface

The *horizon* computer program, developed by Shiono et al. (1987), is used to generate the gridded boundary surface of the model. This program determines the optimal shape of a geological boundary from a set of data consisting of height-data and dip-data. The height data may include inequality constraints as well as normal equality constraints. These types of data are expressed as

$$a - \varepsilon \leq z_i \leq a + \varepsilon$$  \hspace{1cm} (3)

$$z_i = b$$  \hspace{1cm} (4)

where $z_i$ is the altitude to be inferred by the program horizon, $a$ and $b$ are observed altitudes, $\varepsilon$ is the error of $a$.

The altitude obtained from the seismic profiles and boreholes are treated in the form of equation (4). On the other hand, the altitude inferred from the residual anomaly is treated in the form of equation (3), to account for the estimation errors.

4. A case study: Osaka Sedimentary Basin

The above-mentioned method was applied to seismic profiles and gravity anomalies in the Osaka sedimentary basin.

4.1 Relation of standard reflectors

The seismic profiles shown in Fig. 3 were interpreted. These data were provided from four organizations: GS lines by the Geological Survey of Japan (Yokokura et al., 1998), HD lines by the Hydrographic Department of Japan (Iwabuchi et al., 1997), HG lines by Yokota et al. (1997) and O 89 lines by Iwasaki et al. (1994). As it is difficult to find continuous reflectors in profiles in the western part of Awaji and in the southern part of Osaka Bay, seismic profiles in the northern and central parts of Osaka Bay were interpreted. Fig. 4 shows the result of correlation between strong reflectors in the NP seismic profiles and drilling logs at GS-K1 site in the NP seismic lines (Geo-Data Information Committee of Kansai, 1998). The synthetic records of PS logging and VSP records are also shown in Fig. 4. It is found that almost all the strong and continuous seismic reflectors in the NP line are definitely correlated to the bases of thick, marine clay beds. Four strong reflectors to top of the basement, namely, the base of Ma-1, Ma 3 and Ma 6, were correlated. Furthermore, a strong and continuous reflector (RH) between the basement and Ma-1 was detected. These five reflectors, considered as “standard reflectors”, were defined and were called simply BS, RH, Ma-1, Ma 3 and Ma 6, upward from the bottom. The standard reflectors were traced to intersecting profiles. Standard reflectors in time sections for GS and O89 survey lines could be identified because both time sections and depth sections are published. Because only depth sections

Fig. 3. Index map of seismic survey lines. Seismic reflectors on NP profile are correlated to layers in stratigraphic column at a GS-K1 boring site.
Fig. 4. Relation between GS-K1 borehole data and NP seismic profile from Geo-Database Information Committee of Kansai (1998). The location of the survey line and boring site are indicated in Fig. 3. (a) P-wave velocity in depth scale, (b) stratigraphic column of GS-K1 modified from Geo-Database Information Committee of Kansai (1998), (c) P-wave velocity in time scale, (d) the synthetic (left) and VSP record (right), (e) time section along NP line. The thick gray lines indicate the “standard reflectors” in text.

are published for HD and HG surveys, identification of standard reflectors was carried out on depth sections. The gaps in reflector were observed at the intersection of two survey lines, due to difference in velocity estimation. Hence, reflectors in the depth profiles were traced by referring to the interpretation of the time section. The depths of five standard reflectors were sampled at horizontal intervals of 250 m.

Fig. 5 shows the depth relationship between the BS reflector and the other standard reflectors. The relations can be expressed with the following linear regression formulae:

\[ y_i = (0.760 \pm 0.005)x - (0.125 \pm 0.010) \cdot (R=0.969) \]  
\[ y_2 = (0.502 \pm 0.004)x - (0.314 \pm 0.009) \cdot (R=0.950) \]  
\[ y_3 = (0.299 \pm 0.003)x - (0.132 \pm 0.006) \cdot (R=0.950) \]  
\[ y_4 = (0.204 \pm 0.002)x - (0.053 \pm 0.005) \cdot (R=0.901) \]

where \( y_i, y_2, y_3, \) and \( y_4 \) are depths (km) of RH, Ma-1, Ma 3 and Ma 6, respectively, \( x \) is the depth (km) of BS. A value with the prefix ± is a standard error. \( R \) is a correlation coefficient. The depth of each reflector has a good correlation with that of BS. This suggests the sedimentary basin has developed due to the systematic tectonic movement.

Fig. 5. Relationship between the depth of top of the basement rocks and bottom of standard layers. Cross, open square, triangle and circle show the depth of RH, Ma-1, Ma 3 and Ma 6, respectively. Dotted, broken, alternate long and short dash and solid lines represent equations (5), (6), (7) and (8) in the text, respectively.
4.2 Relation between residual gravity anomalies and altitude of basement

Fig. 6 indicates Bouguer anomalies and observation stations. The Bouguer anomalies at 4875 points were compiled from Komazawa et al. (1996) and Inoue et al. (1998). The reduction density for Bouguer and terrain correction was assumed to be 2.45 g/cm$^3$, which was the average of the subsurface density in this region (Shichi et al., 1995).

Bouguer anomalies were separated into two components: regional gravity anomalies and residual anomalies.

Fig. 6. Distribution of gravity observation and contour map of the Bouguer anomalies compiled from Komazawa et al. (1996) and Inoue et al. (1998). The reduction density for Bouguer and terrain correction is 2.45 g/cm$^3$. Solid circles indicate sites of gravity observations. Numerical values show observed Bouguer anomalies in mgal. A contour interval is 1 mgal.

Fig. 7. Distribution of gravity observation sites where the altitude of the basement rocks is known. Numerical values in figure indicate the altitude of the basement rocks in km.
Fig. 7 shows observation stations of gravity at 152 points where the altitudes of the basement rocks are known. These data were used to determine coefficients in the equation (1). The correlation coefficients for \( m \geq 3 \) are higher than 0.95 (Table 1). In this paper, the polynomial for \( m=4 \) was used in the same way as described by Inoue et al. (1998). The list of coefficients is shown in Table 2, and Fig. 8 indicates the regional gravity trend.

### Table 1. List of correlation coefficients in various \( m \) of the equation (1).

<table>
<thead>
<tr>
<th>( m )</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.9372</td>
</tr>
<tr>
<td>3</td>
<td>0.9553</td>
</tr>
<tr>
<td>4</td>
<td>0.9655</td>
</tr>
<tr>
<td>5</td>
<td>0.9656</td>
</tr>
</tbody>
</table>

### Table 2. List of coefficients and standard errors of equation (1), assigning forth-order of polynomial surface for the regional anomalies.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Standard error</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C )</td>
<td>14.052</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>9.488</td>
</tr>
<tr>
<td>( A_{10} )</td>
<td>( 4.670 \times 10^3 )</td>
</tr>
<tr>
<td>( A_{11} )</td>
<td>( 7.467 \times 10^3 )</td>
</tr>
<tr>
<td>( A_{12} )</td>
<td>( -1.117 \times 10^3 )</td>
</tr>
<tr>
<td>( A_{13} )</td>
<td>( -4.053 \times 10^3 )</td>
</tr>
<tr>
<td>( A_{14} )</td>
<td>( 2.698 \times 10^3 )</td>
</tr>
<tr>
<td>( A_{20} )</td>
<td>( -7.001 \times 10^4 )</td>
</tr>
<tr>
<td>( A_{21} )</td>
<td>( -7.810 \times 10^4 )</td>
</tr>
<tr>
<td>( A_{22} )</td>
<td>( 0.725 \times 10^4 )</td>
</tr>
<tr>
<td>( A_{23} )</td>
<td>( -0.498 \times 10^4 )</td>
</tr>
<tr>
<td>( A_{24} )</td>
<td>( -7.621 \times 10^4 )</td>
</tr>
<tr>
<td>( A_{30} )</td>
<td>( -1.431 \times 10^5 )</td>
</tr>
<tr>
<td>( A_{31} )</td>
<td>( -7.784 \times 10^5 )</td>
</tr>
<tr>
<td>( A_{32} )</td>
<td>( 1.280 \times 10^5 )</td>
</tr>
<tr>
<td>( A_{33} )</td>
<td>( 1.840 \times 10^5 )</td>
</tr>
</tbody>
</table>

Fig. 8. Contour map of the regional gravity trend in the Osaka sedimentary basin. Numerical values in figure show regional gravity anomaly in mgal. A contour interval is 1 mgal.
Modeling of the underground structure in the Osaka sedimentary basin

Fig. 9. Relationship between the gravity anomalies and altitudes of the basement rocks. Open circle and cross mark indicate the residual anomaly and the Bouguer anomaly, respectively. A solid line in figure represents equation (9) in the text. Broken lines give a standard deviation.

Fig. 9 shows the relationship between the altitudes of the basement rocks and the gravity anomalies. An open circle (○) and a cross (+) indicate the residual gravity anomaly and observed Bouguer anomaly, respectively. Substituting the coefficients of Table 2 in the equation (2) gives

\[ z = (0.105 \pm 0.061) g_L (R=0.965) \]  

where \( g_L \) is the residual anomaly (mgal). The solid line in Fig. 9 corresponds to the equation (9). The strong correlation is observed between the residual gravity anomaly and the altitude of basement rocks. The root-mean-square (RMS) is 0.245 km, indicating that the altitudes of the basement rocks can be estimated from the residual gravity anomalies within an error of 0.245 km.

4.3 Boundary surfaces of the constructed model

A four-layered model was constructed: A layer from the surface to the base of Ma 6, B layer from the base of Ma 6 to the base of Ma-l, C layer from the base of Ma-l to the top of the BS, and D layer representing basement.

In the first step, two data sets were prepared to construct the model. One was a set of altitudes derived from the seismic profiles and borehole data. This type of data was treated as “equality constraints” for the horizon program.

The other was a set of altitudes inferred from the residual anomalies. This type of data was treated as “inequality constraints” for the horizon program.

In addition to altitudes of BS inferred from the equation (9), data sets of the altitudes for Ma-l and Ma 6 were obtained by substituting the altitudes of BS for \( x \) in the equations (6) and (8). The parameter of inequality constraints for the horizon program, \( a \) and \( \varepsilon \) are summarized in Table 3.

Fig. 10 (a to c) shows the distribution of input data for the horizon program: BS (a), Ma-l (b) and Ma 6 (c), respectively. Using data sets, altitudes of BS, Ma-l and Ma 6 were calculated for 61 x 46 grid nodes at 1 km intervals. Fig. 11 shows the results of estimation.

Table 3. List of parameters for gridding of the boundary surface.

<table>
<thead>
<tr>
<th>Boundary</th>
<th>( a )</th>
<th>( \varepsilon (\text{km}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ma 6</td>
<td>Equations (8) and (9)</td>
<td>0.050</td>
</tr>
<tr>
<td>Ma-l</td>
<td>Equations (6) and (9)</td>
<td>0.123</td>
</tr>
<tr>
<td>Basement rocks</td>
<td>Equation (9)</td>
<td>0.245</td>
</tr>
</tbody>
</table>

5. Discussion

To verify the constructed model, observed gravity anomalies were compared with values calculated from the model.

The information of the density is needed to calculate the gravity of the model. There are several methods to estimate the density: direct measurement of the rock sample, estimation from density logging, and inference from the gravity anomaly. The density was estimated from the P-wave velocity based on the elastic theory of Gassmann (Gassmann, 1951), as there is a large amount of seismic data. The Geo-Data Information Committee of Kansai (1998) summarizes the procedures as follows.

\[ \rho = (1 - n) \rho_s + n \rho_w \] (10)

\[ \log_{10} n = -0.000563 V_p0 + 0.595 \] (11)

\[ V_p0 = V_p - 355 D^{-0.175} + 816 \] (12)

where \( \rho \): density (g/cm\(^3\)), \( \rho_s \): density of particle (the value of granite : 2.66 g/cm\(^3\)), \( \rho_w \): density of water (g/cm\(^3\)), \( n \): porosity, \( V_p \): P-wave velocity (m/sec), \( V_{p0} \): corrected P-wave velocity (m/sec), \( D \): depth (m). \( \rho_w \) is taken from the table of Tanishita (1997) that assumes the temperature gradient of 3°C/100 m, and 15°C at the surface. It should be noted that the increase of density due to the overburden is compensated for by the equation (12).

The density value of 2.55 g/cm\(^3\) was used for the basement rocks, as estimated by Geo-Database Information Committee of Kansai (1998). In order to estimate densities of A, B and C layers, equations (10)-(12) and the interval velocity derived from velocity analysis were used.
Fig. 10. Distribution of input data for surface determinations. Solid circles show the altitudes obtained from borehole data and seismic profiles. Crosses show the altitudes derived from the residual anomalies. (a) top of the basement rocks. (b) base of Ma-1.
Modeling of the underground structure in the Osaka sedimentary basin

Fig 10. (c) base of Ma 6.

Fig. 11. Contour map of boundary surface. Numerical values in figure show altitudes in km. A contour interval is 0.1 km. Thick red lines in land indicate active faults modified from Geographical Survey Institute (1996 a-c). Solid purple lines in the Osaka Bay denote submarine geological structure modified from the Hydrographic Department of Japan (1995). (a) top of the basement rocks.
Fig. 11.(b) base of Ma-1.

Fig. 11.(c) base of Ma-6.
Fig. 12 shows the relationship between the estimated density and the depth of the layer. The correlation coefficient between the depth and density is 0.205 in A layer, 0.404 in B layer and 0.705 in C layer. In the case of C layer, the density tends to increase as the depth advances. The C layer is the lowest deposit in the Osaka basin and there is a possibility that the effect of overburden is not sufficiently corrected by the equation (12). Therefore, in this study, it was assumed that the density changes with the depths in the C layer. Considering that the relation between the depth and the P-wave velocity was expressed as an exponential function in the equation (12), an experimental equation was obtained as follows:

\[ P_C = (0.753 \pm 0.109) \log D_p - (0.156 \pm 0.032) \quad (R=0.747) \] (13)

where \( P_C \) is the density (g/cm\(^3\)) of C layer, \( D_p \) is the depth (m) of the bottom of C layer. Table 4 summarizes the density values used in the gravity calculation.

The gravity anomaly is calculated in two steps. At first, rectangular elements are divided into triangular ones based on the algorithm of Ryoki (1996). In the next step, gravity anomalies for each triangle are calculated using the method of Götzte and Lahmeyer (1988).

Fig. 13 indicates the difference between observed gravity anomaly and calculated value. The average of this difference was calculated to be \(-0.0936 \pm 0.0716\) mgal. It is noted that there were no gravity data in the northwestern part of the study area, off Ashiya and the Akashi Straits, as shown in Fig. 6. Positive values around Takaishi and Izumi-Otsu indicate the existence of subsurface sediments with high density. There are other positive values along faults. This may be due to problems related to grid approximation in this study; a grid interval of 1 km is too wide to express the geological structure in this area, and the reverse fault can not be approximated in the present model.

The RMS of the difference of observed gravity and calculated gravity from the constructed model was 3.79 mgal, including the above-mentioned area. This low value of difference validates the proposed geological model. This model is useful as an initial model for the gravity analysis. Further modification of the model may be needed in order to fit the calculated gravity anomaly to the observed one more accurately. This will be discussed in a separate paper.
6. Conclusion

A three-dimensional model was constructed, based on geological interpretation of seismic profiles and gravity anomaly.

Seismic reflectors were correlated to the stratigraphy from deep borehole data. The depths of sedimentary layers in the Osaka sedimentary basin have linear relationship with that of the basement rocks.

In the gravity analysis, the regional gravity trend was subtracted from the Bouguer anomaly. The residual gravity anomaly has a good correlation with the altitude of the basement rocks.

The RMS of the difference of observed gravity and calculated gravity from the constructed model was 3.79 mgal. This low value of difference validates the proposed geological model. There was the difference due to local anomaly of density, as seen around Takaishi and Izumi-Otsu. Also, the positive difference of gravity along the faults is related to the interval of grid and inadequate expression of the geological structure in this model.

The constructed model has been validated using the constraints obtained from the geological survey, the seismic reflection survey and the observed gravity anomaly.

Acknowledgments

We express our deep thanks to Professor Shiono Kiyoji and Associate Professor Mitamura Muneki of Osaka City University for reviewing and improving the manuscript. We wish to thank Dr. Yokokura Takanobu of the Geological Survey of Japan, senior inspector Iwabuchi Yo of the Hydrographic Department of Japan, Dr. Hujita Kazuo of Fault Research Data Center, Director Iwasaki Yoshinori and Dr. Kitada Naoko of Geo-Research Institute for permitting the use of various sets of information. We are also grateful to Associate Professor Masumoto Shinji of Osaka City University and Uda Hideo of Osaka City University for their assistance in analysis by computer. The comments and suggestions by Associate Professor Venkatesh Raghavan of Media Center, Osaka University and Pathak Dinesh of Osaka City University were useful in improving the manuscript.

Financial support was provided by the special scholarship for doctoral course students of Osaka City University.

References

Gassmann, F. (1951) Elastic waves through a packing of
Modeling of the underground structure in the Osaka sedimentary basin

Geo-Database Information Committee of Kansai (1998) *Ground of Kansai area especially Kobe and Hanshin*, Osaka, Yodogawa kogisya, 270 p. **


Hydrographic Department of Japan (1995) Submarine Structural Chart -Akashi Kaikyo and Osaka Wan-, *Hydrographic Department of Japan*. **


* in Japanese with English abstract  
** in Japanese  

Manuscript received August 31, 1999.  
Revised manuscript accepted February 28, 2000.