Strong Motion Prediction based on the 3-D Basin Structure and Inhomogeneous Source Process of Hypothesized Kego Earthquake in Fukuoka, Japan

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ABSTRACT :

On March 20, 2006 the City of Fukuoka were jolted by the West off Fukuoka Prefecture earthquake of M_J 7.0 and moderate damage to structures (around 300 heavy damage buildings) were observed. First the seismic records of K-NET, KiK-net, the JMA network, and Fukuoka Prefecture network during this earthquake were collected and analyzed. We then constructed a clear asperity source model on the fault plane. We use a three-dimensional (3-D) deep basin model based on the S-wave velocity structures at four sites, geological data, topographical information, and gravity data. We used forward modeling technique with an assumption of a single asperity located at the southeast of the hypocenter, which is derived from a multi-window kinematic source inversion by Suzuki and Iwata. We found a high speed peak slip velocity in this relatively small asperity. The resultant simulated strong motions show quite similar waveforms with the observed ones. Next we estimated broadband strong ground motions in Fukuoka City by using an improved version of the 3-D basin structure based on a detailed map of gravity anomaly. We simulated strong ground motions during the hypothesized Kego earthquake using hypothesized rupture scenarios derived from the multi-asperity source model obtained for the Hyogo-ken Nanbu (Kobe) earthquake of 1995. The result of our simulation shows that we have to prepare for a severe disaster in the downtown Fukuoka, once such an event would occur. The detailed distribution of high peak ground velocity (PGV) and maximum values inside the high value zone strongly depend on the rupture scenario, however, the downtown Fukuoka is always the region of high PGVs.

KEYWORDS: Strong motion prediction, hypothesized earthquake, asperity, 3-D basin

1. INTRODUCITON

On March 20, 2005, the West off Fukuoka earthquake of magnitude M_J 7.0 occurred at 20km offshore from the port of Fukuoka, and moderate damage took place in and around Fukuoka City, which has the population of 1.4 million. It is very important in urban disaster prevention of Fukuoka City in future to clarify the characteristics of the strong motions during this West off Fukuoka earthquake. In addition, after the earthquake geophysical investigations inside the Hakata Bay, the main port of Fukuoka City, were performed to reveal that the seismogenic fault of the West off Fukuoka earthquake is actually connected to the well-known active fault that runs through downtown Fukuoka, the so-called Kego fault. Because of this connection the risk due to the Kego fault become a primary seismic threat to the safety of Fukuoka City. This it is very important to grasp what kind of damage would occur beforehand for disaster prevention of Fukuoka City and surrounding regions.

It is our first task to learn as much as we can from the strong motion data observed during the West off Fukuoka earthquake. To this end we first collected and analyzed strong motion data of K-NET, KiK-net, the JMA network, and Fukuoka Prefecture's Seismic Intensity seismograph network. Then we derive a distinctive asperity model to explain these observed data based on the kinematic 3-D FDM code of Graves (1996). In

Fukuoka city area, three-dimensional (3-D) basin structure model has already been built by Nakamichi and Kawase (2002) and so we used their model as a starting model. As for the source model of the West off Fukuoka earthquake, several inversion models were proposed and we refer to the one obtained by Suzuki and Iwata (2006) who derived it based on the empirical Green's function method. Starting from an initial asperity model based on the inversion result of Suzuki and Iwata, we tried to improve the matching with data by using the 3-D basin structure of Nakamichi and Kawase (2002) and a Kostrov type slip velocity function within an asperity, as successfully performed for Kobe (Kawase et al., 2000). After tens of trial-and-error forward modeling, we have reached the best solution that can reproduce most of the observed records in the target area. However, there are a couple of observation points where we cannot see any improvement because of the discrepancy in the 3-D basin structure below these sites. Therefore, we judge that we need to re-evaluate the Nakamichi and Kawase model.

As a final step toward our goal we calculate 3-D responses of the Fukuoka basin for the hypothesized Kego fault. To do so we use a detailed abnormal gravity map in Fukuoka obtained by Nishijima et al. (2005) to improve the basin structure of Nakamichi and Kawase. We then simulate strong motions in Fukuoka City based on the fault model of Kobe suggested by Matsushima and Kawase (2006). We expect that this prediction will be utilized for the assessment of the whole damage impact of Fukuoka City due to the hypothesized Kego earthquake and for the development of policies for disaster prevention.

2. OBSERVED STRONG MOTIONS OF THE WEST OFF FUKUOKA EARTHQUAKE

The mechanism and rupture pattern of the West off Fukuoka earthquake are basically the same as those of typical inland earthquakes in the northwestern Japan. Figure 1 shows aftershock distribution determined by the Institute of Seismology and Volcanology, Faculty of Sciences, Kyushu University (http://www.sevo.kyushu-u.ac.jp/index-e.html). It shows clearly that the strike is 35 degree southeast, which corresponds to the strike-slip mechanism determined by moment tensor inversion (http://www.fnet.bosai.go.jp/freesia/event/hypo/joho.html). As shown in this figure, the Kogo fault is running from northwest to southeast inline with the strike of the Wet off Fukuoka earthquake. We first report here the basic features of strong motion records observed in Fukuoka City.

We have only one K-NET observation station (FKO006) installed in Tenjin, downtown Fukuoka. The Japan Meteorological Agency (JMA) deployed a seismic intensity seismograph at the Fukuoka regional meteorological observatory in Ohori, Chuo-ku. In addition to these nation-wide network stations, the seismic intensity seismographs installed by Fukuoka Prefecture were in operation in each district as well as small towns and villages. The strong motion records of these seismic intensity seismographs in Fukuoka were collected except for Higashi-ku where new aftershock records were overwritten on the main shock record. As for Higashi-ku, we can use a record at Kyushu University hospital as a substitute since they are located closely

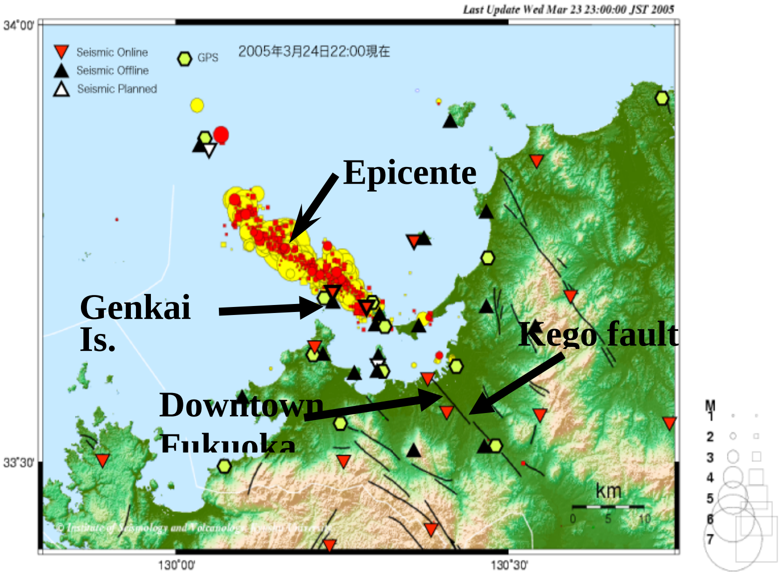

Figure 1. Location of the main shock and aftershocks (within 3 days) determined by the Institute of Seismology and Volcanology, Faculty of Sciences, Kyushu University.

each other. In addition to these data, one main shock observation data of a private base-isolated building (CTI Fukuoka Building), situated very closely to the Kego fault in Chuo-ku, were obtained and analyzed here. Figure 2 shows these observation points together with the depth distribution of shallow Quaternary layers (Itoh and Kawase, 2001). Two straight lines here show the Kego fault, which runs through downtown Fukuoka. Shallow layers are thick (~50m) in the northeastern side of the Kego fault.

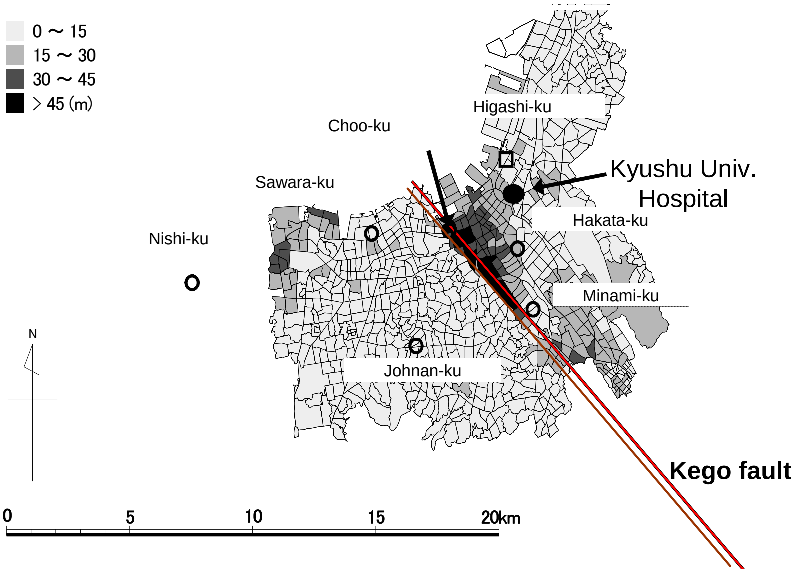

Figure 2. Strong motion stations of Fukuoka Prefecture in Fukuoka City and Quaternary layer depth (after Ito and Kawase, 2001).

Table 1 summarizes basic information of these observed stations. When we plot observed records we found that NS components are similar to each other among three stations near the Kego fault, while EW components become different a couple of seconds after the onset of S-wave. Records observed in CTI building are similar to those at Chuo-ku (FKOS01) but a little bit larger in amplitude. When we look at the frequency content at three observation stations, we found that FKO006 does not have the power of FKOS01 in the period range of 0.7 to 1.5 seconds and that the records at CTI Fukuoka Building have even larger power with the prominent 0.5 second peaks in both NS and EW components. These 0.5 second peaks are derived from the wave packet seen just after the S wave arrival, especially in the EW component, while the largest peaks at around 1.5 seconds seen in all the NS components are derived from the directivity of an asperity, as shown later in this paper.

Table 1. Information of stations in Fukuoka City

Code	Type	Lat.	Long.	PGA (Gal)	PGV (cm/s)	JMA Intensity
FKOS01	Intensity seismograph, Chuo	33.5875	130.3917	288.4	64.4	5.73
FKOS02	ditto. Sawara	33.5864	130.3578	238.5	29.0	5.28
FKOS03	ditto. Nishi	33.5697	130.2794	231.2	21.2	5.23
FKOS04	ditto. Johnan	33.5494	130.3775	361.8	15.6	4.72
FKOS05	ditto. Minami	33.5617	130.4286	141.1	22.5	4.80
FKOS06	ditto. Hakata	33.5817	130.4217	138.1	30.5	4.93
FKOS07	ditto. Higashi	33.6111	130.4164	311.4	-	5.50
FKO006	K-NET Fukuoka	33.5936	130.4008	276.5	59.5	5.54
EDF___	JMA Fukuoka(Ohori)	33.5791	130.3785	189.1	29.5	5.15
CTI	CTI building	33.5852	130.3937	488.8	72.1	5.99

3. APERITY MODEL OF THE WEST OFF FUKUOKA EARTHQUAKE BY 3-D FDM

We determined source process of the main shock by using the model from Suzuki and Iwata (2005) as an initial model. They used empirical Green's function method for inversion, while we generate synthetic velocity waveforms by 3-D FDM with the 3-D underground structure, which is based on a Fukuoka basin model of

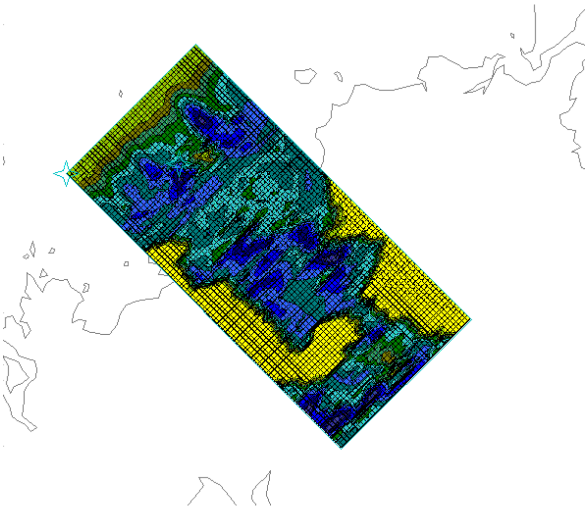

Figure 3. Modeled region, source location, and stations for comparison.

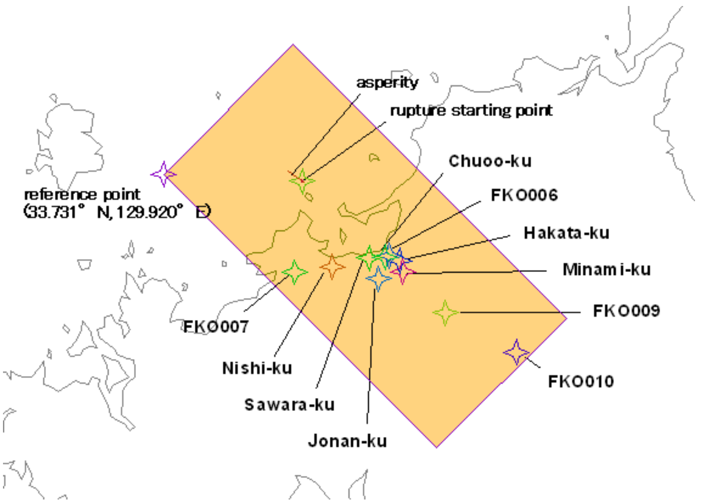

Figure 4. Modeled region, source location, and stations for comparison.

Nakamichi and Kawase (2002) as shown in Figure 3. Starting from the initial model from Suzuki and Iwata (2005) we try to improve fitting of synthetics to the observed seismograms assuming a single asperity model without background slip as we succeeded to derive our original source model for the Hyogo-ken Nanbu (Kobe) earthquake (Kawase et al., 2000). We apply a band-pass filter from 0.5 Hz to 3 Hz to the observed velocity waveforms used as target. We also apply a low-pass filter with the cut-off frequency of 3Hz to the synthetics calculated by 3-D FDM.

We use 3-D FDM code developed by Graves (1996) with a grid spacing of 0.08 km, a time step of 0.004 s, and total steps of 5,000 (or 6,250 for the final model). The topmost layer of 3-D FDM is assumed to have 600 m/s in terms of S-wave velocity, which corresponds to the engineering bedrock of Pliocene or older and the small topography of the region is totally neglected. The modeled region is 36 km in width, 76 km in length, and 20 km in depth, 45 degrees rotated clockwisely from the north as shown in Figure 4. Ten target stations are also shown in Figure 4. Table 2 lists the assumed basin structure, while Table 3 does the structure of the upper crust assumed as a surrounding medium. As we mentioned we used Suzuki and Iwata's model (2005) determined by the empirical Green's function method as an initial asperity model.

Table 2 Parameters of the Fukuoka basin

layer	Vp (㎞/sec)	Vs (㎞/sec)	density (g/cm^3)	Q	thickness ratio
1	1.90	0.60	1.90	30	0.09
2	2.60	1.10	2.10	50	0.29
3	3.50	1.70	2.30	80	0.62

Table 3 Parameters of the surrounding rock

layer	Vp (km/sec)	Vs (km/sec)	density (g/cm^3)	Q	depth (km)
1	3.2	2	2.1	100	0.1
2	5.15	2.85	2.5	200	2
3	5.5	3.2	2.6	400	5
4	6	3.46	2.7	600	18
5	6.7	3.87	2.8	700	34.56

First we investigate the influence of directivity to the waveforms at stations along strike. A rupture starting point of the asperity in the initial model, shown in Figure 5 as an open star only yields backward directivity to the stations along strike, while observed waveforms seem to have asperity pulses caused by forward rupture directivity. To confirm the effects of directivity we compare waveforms of the initial model with those with a rupture starting point varied from southeast (right) to northwest (left) as shown in Figure 5 as a solid diamond. We found that the initial prominent pulse observed at stations such as FKO006 cannot be seen unless the rupture starting point is located northwest of the asperity. After fixing the rupture starting point, we try to match the whole velocity waveforms by tuning the size of the asperity and slip velocity function. Since the duration time of rupture seems too long, the size of the asperity may be too large. Actually, a smaller asperity is identified in the inversion of other researchers. So we made the width of the asperity one half of the initial model by cutting 1/4 of its top and bottom portion. Figure 5 shows that smaller asperity as a red rectangle. Then, we looked at the swing-back pulse and the last part of the waveform to tune up the slip velocity time

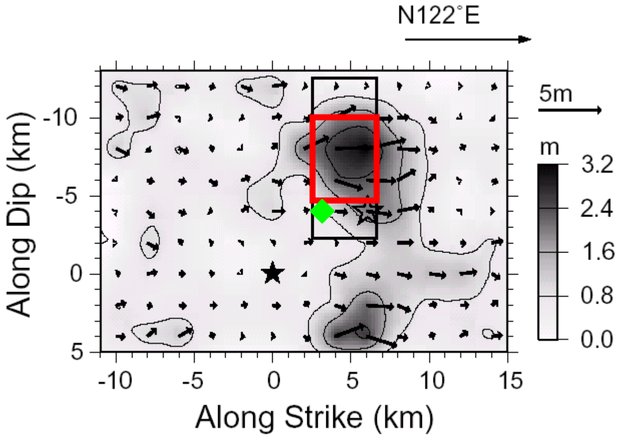

Figure 5. The initial single asperity rupture scenario (solid rectangle), final scenario (red rectangle) and their rupture starting points (open star and green diamond) on top of the final slip distribution of Suzuki and Iwata (2006).

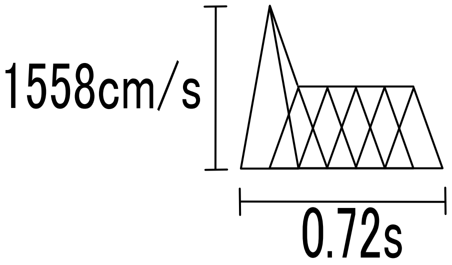

Figure 6. The final slip velocity function obtained by matching the whole waveforms of several stations in Fukuoka. The resultant total seismic moment is 3.40E+18 N m.

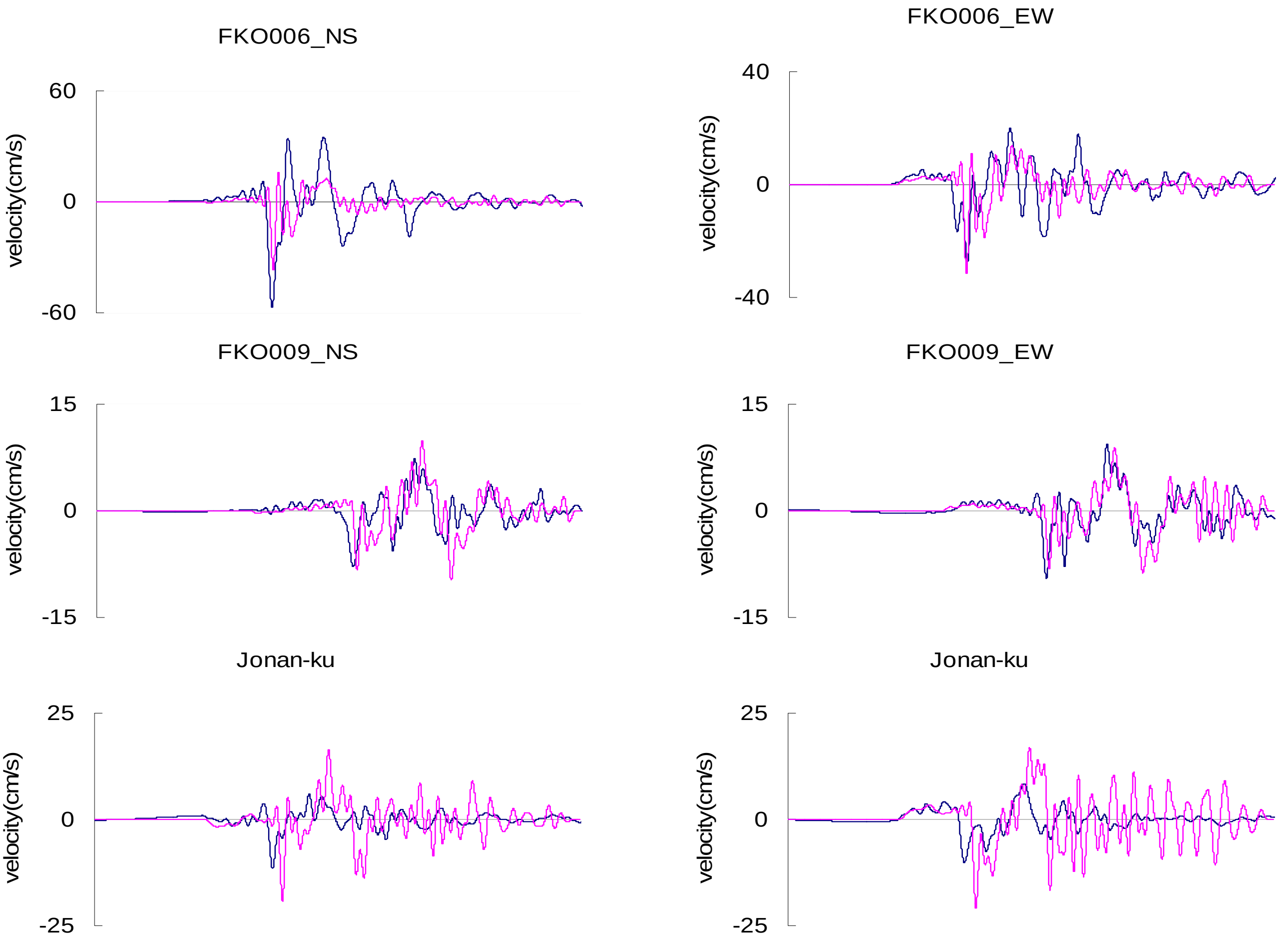

Figure 7. Synthetic velocity waveforms of the final model shown in Figures 5 and 6 in comparison to the observed velocity seismograms (blue: observed, red: synthesized).

function. After dozens of trials with different slip velocity time functions we found the best slip velocity model as shown in Figure 6. In Figure 7 we compare synthetic waveforms of this model with the observed. Here we reduce the seismic moment to 1/2 of the initial one but we consider the amplification of shallow Quaternary layers. Matching with the observed records is quite satisfactory at most stations except for the one at Jonan-ku (FKOS04), where we may have too soft or too deep basin structure than the reality.

4. RE-ESTIMATION OF 3-D BASIN STRUCTURE FOR THE KEGO EARTHQUAKE

As Nakamichi and Kawase (2002) did, first we set contour lines of elevation of 70 meters as the basin border based on Geological Map of Japan. Nakamichi and Kawase read gravity anomalies value by looking at the gravity anomaly map of 1:200,000 for the whole Kyushu region. However, the Bouguer anomaly values of the detailed gravity map for Fukuoka City area by Nishijima et al. (2005) are different and seem more reliable because it shows clearly an abrupt change at the Kogo fault. We read a contour map of Nishijima et al. (2005) to create a figure as shown in Figure 8. The area that we read is 17.0km in length and 18.5km in width. Since the area of this detailed gravity exploration does not fully cover the target area of strong motion simulation, we referred to an abnormal gravity map of a 1:200,000 and connect them as smooth as possible.

To transform gravity anomalies into basin depths we refer to our velocity exploration study by array measurements of microtremors performed at four sites in Fukuoka City. Based on the observed basin depths and the gravity anomalies value at their points we made a relationship in Fukuoka City as shown in Figure 9. Then we can translate the gravity anomaly data into the basin depth. The final basin depth contour proposed here is shown in Figure 10. The analysis area is 40km in length, 32km in width, 20km in depth, the same as in Nakamichi and Kawase (2002). The northwest corner at (33.5511°N, 130.1707°E) is used as a control point of the model. The basin depth contour map is rotated 45 degrees from the North clockwisely when we see a rectangular analysis box of ground. The same layered basin structure and the surrounding rock formation as already listed in Tables 2 and 3 are assumed.

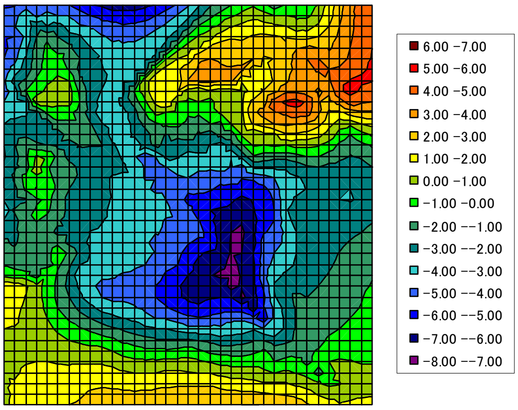

Figure 8. Residual Bouguer anomaly map (after Nishijima et al. 2005).

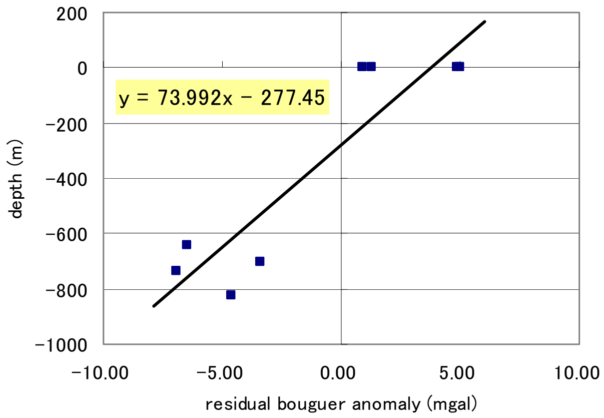

Figure 9. Relationship of gravity anomalies and basin depth

5. PREDICTION OF STRONG GROUND MOTIONS

As for the fault rupture model for the hypothesized Kego earthquake we use two different multiple-asperity models as shown in Figure 11, both of which are derived from the fault model of Matsushima and Kawase (2006) obtained for the Hyogo-ken Nanbu (Kobe) earthquake of 1995. Case 1 uses the same location and rupture pattern of Kobe, although only four asperities are considered among five asperities in Matsushima and Kawase (2006) because the length and hence the seismic moment is smaller for the Kego earthquake. Case 2 uses the same asperities but reversed rupture directions. The slip velocity functions are the same as in Matsushima and Kawase (2006) as shown in Figure 12. The total seismic moment of four asperities is assumed to be 6.47E+18 N m, Mw6.4.

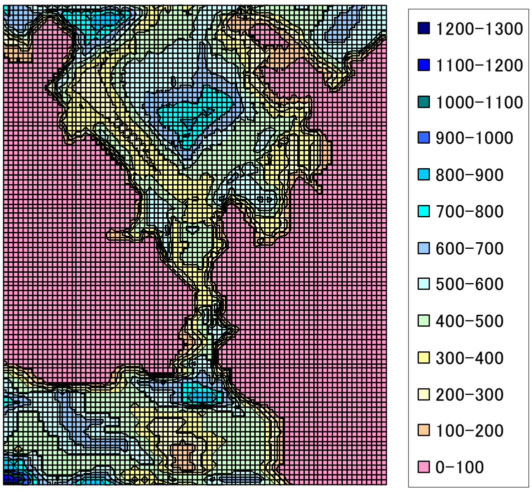

Figure 10 New basin depth contour map.

We plot synthesized waveforms at FKO006, downtown Fukuoka, in Figure 13 as an example and two PGV contour maps in Figure 14 for the Case 1 scenario. We found that the PGVs of our prediction reach more than 100 cm/s just above the shallower asperity, in the direction of rupture propagation. PGVs are higher for fault normal component along the strike of the fault, as is always the case for PGV of asperity pluses due to strike-slip faults. Since the highest PGV area is controlled by the asperity pulse due to directivity, if the rupture direction is opposite, that is, in Case 2, the position of the highest PGV area will be shifted toward the forward rupture direction.

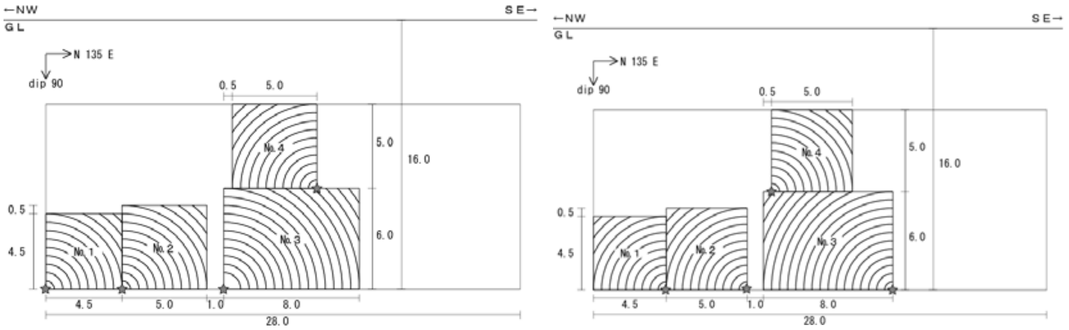

Figure 11. Multiple-asperity models of the assumed Kego earthquake (left: Case 1, right: Case 2).

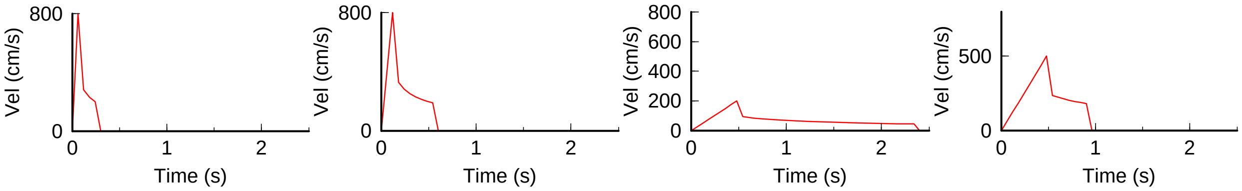

Figure 12. Slip velocity functions of the assumed asperities No.1 to No.4.

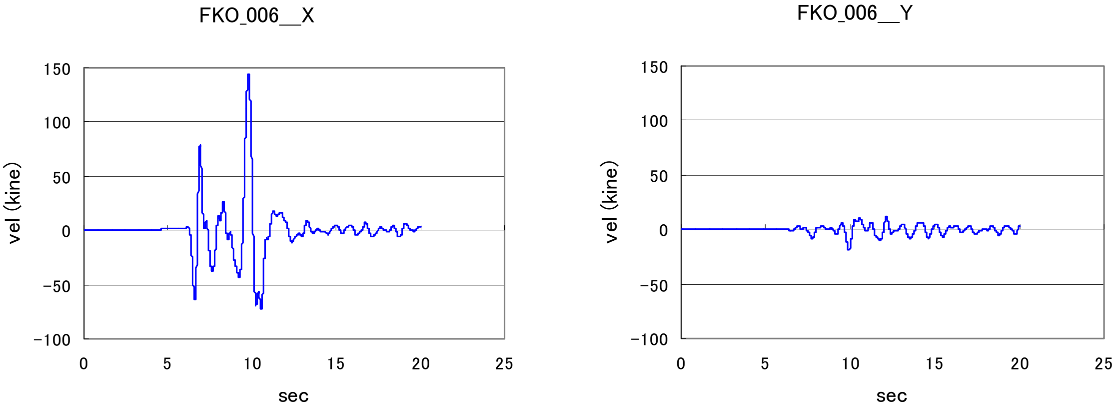

Figure 13. Synthetic velocity waveforms at FKO006 for Case 1 scenario
(left: fault normal component; right: fault parallel component).

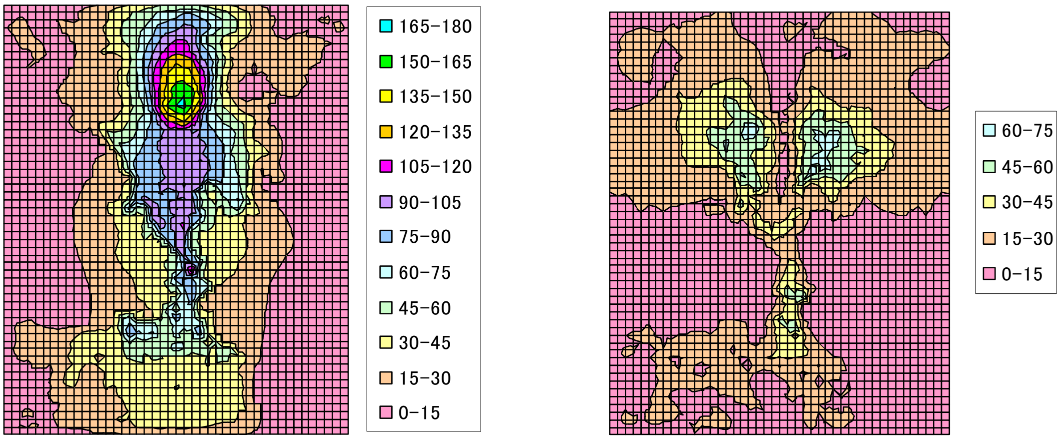

Figure 14. PGV contour map of Case 1(left: fault normal component; right: fault parallel component)

5. CONCLUSION

We had shown the importance of asperities and the 3-D basin structure in strong motion simulation in the epicentral region of inland earthquake taking the Fukuoka City as an example. We have shown that quite a sharp increase of slip velocity is mandatory to reproduce observed asperity pulses at stations along strike of the fault. Then we construct our basin model based on the recent Bouguer Anomaly survey and use rupture scenarios derived from that of the Hyogo-ken Nanbu (Kobe) earthquake. As a result we found that we will have a high PGV region along the Kego fault, just above the shallow asperity. When rupture direction changes the location of a high PGVs will be shifted. PGV in the center of Fukuoka City would be quite large irrespective of the rupture direction and so we should prepare for devastating damage in downtown Fukuoka.

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