

# STRONG MOTION PREDICTION FOR INLAND EARTHQUAKES IN FUKUOKA CITY AND YATSUSHIRO CITY, JAPAN AND THEIR DAMAGE IMPACT TO BUILDINGS

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# SUMMARY

We estimate structural damage of Fukuoka City and Yastushiro City in Kyushu, Japan for potentially dangerous earthquakes based on the strong ground motions evaluated by a hybrid technique. We construct the 3-D basin structures below these cities by using a geological map and a gravity anomaly map, together with S-wave velocity structures at several points inside the basin. Then we use our hybrid simulation technique to estimate broadband strong motions in these cities for a hypothesized inland earthquake of magnitude 7 class with several different rupture scenarios. Based on these ground motions and damage evaluation models of buildings we predict the whole damage of these urbanized areas.

# INTRODUCTION

When considering earthquake disaster prevention of urbanized areas before it occurs, it is important to delineate the whole picture of possible disasters. This is because suitable countermeasures cannot be taken if sufficiently accurate prediction is not made. However, in the urban risk estimation, it has not been easy to predict strong ground motions and the damage of buildings by using detailed quantitative techniques because of huge necessity of information for a large-scale city. Therefore, for most of the cases a simple method is employed based on empirical results such as regression relationships derived from actual measurements [1]. As long as a future event is expected to be a similar one that has already occurred, such an empirical method seems effective. In fact for many future events in a long time span, we can expect such empirical formula may provide reasonable estimate on the average. However, through energetic research activities after the 1995 Hyogo-ken Nanbu earthquake it is shown clearly that highly accurate prediction can be performed only if we take into account the detailed rupture process on the fault and the wave propagation effect inside a deep basin structure since ground motions are strongly controlled by these effects [2][3]. We should emphasize here the importance of predicting high amplitude velocity pluses in the near field (the so-called "killer pulse") because that is the primary source of near-source

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disaster of inland earthquakes. Nonlinear building damage prediction models using strong motion waveforms are also needed, by which we can explain quite well the observed damage distribution [4].

In this paper, the strong ground motions in Fukuoka City and Yatsushiro City both in Kyushu, Japan are first predicted using the technique of quantitative strong motion prediction that takes advantage of the latest seismological achievements. Then based on a set of numerical structure models for different construction types, number of stories, and construction age, we delineate urban earthquake disaster scenario in these cities. As a result, although there seems to be a large difference of damage due to strong motion levels for different rupture patterns, we predict that we must expect serious damage in the central part of Fukuoka City and in the eastern part of Yatsushiro City. Japan.

## METHOD OF STRONG MOTION PREDICTION

We can classify the methods of predicting strong motions into three types, the empirical method, the semi-empirical method, and the theoretical method. The empirical method extracts characteristics of a seismic motion from many observed records by the regression analysis. As mentioned above, the empirical prediction is expected to be satisfactory on the average as long as we have sufficient data. However, it is difficult to reflect the influence of the heterogeneity of the source and site because it depends on the statistical properties of many strong motions. On the other hand, the theoretical method expresses all of these characteristics by a physical model of the source, path, and site. The effect of rupture pattern will be reflected through the use of representation theorem with Green's function evaluated analytically or numerically. Since all the information on the detailed underground structure that controls a high-frequency component of ground motion cannot be given in deterministic manner, there is a maximum frequency limit in accuracy. Therefore, the semi-empirical method is invented in which we substitute Green's function with a record of a small earthquake observed at a target site. Since we can reflect the characteristics of a realistic earthquake motion as well as the rupture propagation pattern on the fault surface, many examples of application have been shown. Recently the statistical Green's function method, which utilizes the average characteristic of observed records for small earthquakes, is frequently used for the prediction since we cannot always find a record at a target site. Although the statistical Green's function method is suitable to express a random wave field, that is, high frequency component, coherent wave summation is not taking place so that it underestimates the amplitude of the velocity pulse with very important predominant frequency around 1 Hz.

Thus we use here a hybrid method [5Kamae][6Pitarka] in which we divide the seismic motion into a low frequency component and a high frequency component at a certain frequency (the so-called "matching" frequency), and we use for a low frequency component the theoretical method and for a high frequency component the statistical Green's function method. In this study, we use the statistical Green's function proposed by Ito et al. [7]. For low frequency we use the Finite Difference Method (FDM) proposed by Graves [8] where we can evaluate the influence of a 3-D basin structure.

The outline of the technique used here is described below. For the statistical Green's function method, we follow the summation technique proposed by Irikura and Kamae [9] using the statistical Green's function of Ito et al. [7] derived as the bedrock motion with the S-wave velocity Vs=1,100 m/sec from observed records in Kyushu, Japan. First they derived spectral and envelope characteristics of the small- and mid-sized earthquakes in order to generate statistical Green's functions. They used K-net records in and around Kyushu. The total numbers of selected sources and sites were 25 and 142, respectively, and the total numbers of accelerograms were 1,278 times 2 horizontal components. They used Boore's envelope function [10] to model the envelope characteristics of observed acceleration. They first determine two essential parameters of his model, namely, the total duration Td and the peak-out time Tr for each record. The tail amplitude ratio relative to the peak amplitude is set to be 1/10. Once they obtain the envelope

parameters Td and Tr, they used a two-step regression analysis to obtain relationships with respect to the JMA magnitude M and the hypocentral distance X. Statistical parameterization of Boore's envelope model here is the first attempt of this sort (before Ito et al., Td and Tr was theoretically assumed). The same regression procedure is used for Fourier amplitude spectra in oder to separate the magnitude term, the Q term, and site coefficients. The reference station they used have a rock formation 4m below the surface with the S-wave velocity of 1,070m/sec.After synthesizing ground motions on the rock outcrop, we consider amplification from this bedrock to the so-called engineering bedrock with Vs=600 m/sec by the 1-dimensional (1-D) wave propagation theory. In Fig.1 we show a comparion of the envelope function with the observed accelerogram. In Fig.2 we show an example of their validation studies on the statisical Green's function for the Kagoshima-ken Hokuseibu earthquake of 1997.



For theoretical calculation we use the 3-D FDM of Graves [8] in the same manner as Matsushima and Kawase (2000) [3] with the grid interval of 0.08km and the time increment of 0.005s. Surface layers of 3D-FDM should have similar S-wave velocities as we assume in the statistical Green's function calculation.

Matching frequency was set to be 1.75 Hz based on the simulation result of the Hyogo-ken Nanbu earthquake. This is higher than usual cases of hybrid method in the past because our four asperity model of Matsushima and Kawase [3] can express 1 Hz or higher coherent waveforms. After summing up two simulation results we estimate the amplification characteristics using the surface structure in Fukuoka or Yatsushiro City and 1-D wave propagation theory to obtain waveforms at the surface with Vs=200 m/sec or less.

#### SOURCE AND GROUND STRUCTURE

As for the source models we basically adopt Matsushima and Kawase's four asperity model as a rupture process of hypothesized earthquake below Fukuoka or Yatsushiro since the Hyogo-ken Nanbu earthquake is the most devastating inland earthquake in 20<sup>th</sup> century in Japan and its rupture characteristics seem to be representative for inland crustal earthquake based on the slip velocity inversion of the Kagoshima-ken Hokuseibu earthquake of 1997 and the Tottori-ken Seibu earthquake of 2000 [11 EOS]. However, since neither the position of asperities nor the position of hypocenter for future earthquakes would be necessarily the same as the Hyogo Nanbu earthquake, we assume several different scenarios each of which has different locations of the hypocenter and asperities.

The Kego active fault system is taken as a primary source for Fukuoka City, which is running directly under Fukuoka City and so it is certain that this fault should be the worst scenario for Fukuoka City. However, the degree of activity of the Kogo fault was estimated to be once in about 13,000, and probability of occurrence within next 30 years is presumed to be less than 1%. The length of the well-studied part of the Kogo fault is about 22km but we assume the fault to extend 3km southeastward to make its total length to be 25km. As for Yatsushiro City we take the Futagawa-Hinagu fault system as a primary target because it is one of most active fault in Kyushu. We must expect to have an earthquake of Magnitude 7 to 7.5 with relatively high probability of 6 % at maximum within next 30 years. The total length of the Futagawa-Hinagu fault is assumed to be 48 km.

As rupture scenarios we assume four scenarios for the Kogo fault. The scenario 1 and 2 are the same cases as the Hyogo Nanbu earthquake (the dip angle is fixed to be 90 degrees) with different direction of rupture propagation. The scenario 3 has different sequence of four asperities and the scenario 4 has two asperities in a shallower part of the fault below Fukuoka City. These rupture processes are shown in Fig. 3. The rupture starts from star symbols. Within asperity the rupture is assumed to spread radially from one bottom corner shown by star symbols( $\bigstar$ : hypocenter,  $\stackrel{\wedge}{\asymp}$ : rupture initiation point for each asperity). We assume pure strike-slip for all the four scenarios. Parameters of four asperities are summarized in Table 1. For the Futagawa-Hinagu fault we use 16 scenarios in order to statistically see the variations due to different rupture scenarios. The basic scenario is the same as the scenario 1 of the Kogo fault shown in Fig.3. In addition to that we use wider asperity distribution scenario as shown in Fig.4. For each asperity distribution we assume two unilateral and two bilateral scenarios with the hypocenter in the northern and southern side. As for the rake angle we assume pure strike-slip and 135 degree cases.



Fig.3 Four scenarios assumed for the Kego fault in Fukuoka

No	Seismic Moment $M_0 \times 10^{18}$ (N $\cdot$ m)	Size L*W (km <sup>2</sup> )	Rupture Start Time (sec)	Total Slip D <sub>0</sub> (m)	Stress Drop Ratio C	Sub- Fault No. N
1	0.62	4.5*5	0.00	0.85	0.90	2
2	1.07	4.5*5	1.79	1.47	1.56	2
3	2.59	8*10	3.70	1.00	0.53	5
4	4.83	8*10	6.25	1.90	1.90	5

 Table 1 Parameters of four asperities



Fig. 4 Widely-distributed four asperity scenario for the Futagawa-Hinagu fault in Yatsushiro.



Fig. 5 The modeled region and the basin structure for Fukuoka City

Fig. 6 The modeled region and the basin structure for Yatsushiro City

Construction of the 3-dimensional basin models in the Fukuoka area and in the Yatsushiro area is performed in the following procedures. First, a basin boundary is set based on geologic maps of each region. Then gravity anormaly contours were digitized and the long-range trend was removed. We compare these gravity anormalies with basin depths obtained by microtremors and use a simple regression coefficient between gravity anormalies and depths to convert the former to the latter. The analysis domains are 40km x 32km x 22km for Fukuoka and 64km x 26.4km x 22km for Yatsushiro, respectively,

as shown in the Figs. 5 and 6. The deepest basin depth of the Fukuoka basin is 1,200m, while that of the Yatsushiro basin is 450m. Parameters of these two basins and the surrounding rock formation are summarized in Tables 2 to 4. As for the surface (Quaternary) layer structures, the two- or three-layered structures derived from boring data are used. Depth distribution of surface layers in Fukuoka is shown in Fig.7.

No.	Vp(km/sec)	Vs(km/sec)	$\rho(g/cm^3)$	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 2 The basin structure of Fukuoaka City

<b>Fable 3</b> The bas	n structure	of Yatsushiro	City
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No.	Vp(km/sec)	Vs(km/sec)	$\rho(g/cm^3)$	Q	Thickness ratio
1	1.42	0.53	1.91	30	0.04
2	1.80	0.68	1.91	30	0.51
3	2.50	1.16	1.91	60	0.45

Table 4 The surrounding rock formation						
No.	Vp(km/sec)	Vs(km/sec)	$\rho(g/cm^3)$	Q	Depth(km)	
1	3.20	2.00	2.10	100	0.10	
2	5.15	2.85	2.50	200	2.00	
3	5.50	3.20	2.60	400	5.00	

2.70

2.80

600

700

18.00

00

3.46

3.87

6.00

6.70

4

5



Fig.7 Depth contour of shallow Quarternary layers in Fukuoka

#### **RESULTS OF STRONG MOTION PREDICTION**

#### Fukuoka City

The peak ground velocity (PGV) distribution on the surface is shown in Fig. 8 for all the four scenarios for Fukuoka City. A thick red lines represent the Kego fault. Due to forward rupture directivity and amplification by the basin and Quarternary structure we observe high PGV areas along the fault, especially in the eastern side of the fault. We have the maximum PGV of about 130 cm/sec for Scenario 1. In Scenario 2, the rupture propagation direction is opposite, that is, backward direction away from Fukuoka, and so it yields only 50 cm/sec at most in Fukuoka. Note that the peak area should show up in southern cities in this case, though. In Scenario 3, the peak region is shifted to south from Scenario 1 with a little smaller level of PGV than Scenario 1. In Scenario 4 very high value of PGV is seen at the northwest side along the Kogo fault with the maximum about 200 cm/sec. This reflects the shallower depths of two asperities below that area.

To see the difference of synthetic velocity seismograms we plot in Fig.9 those calculated at the center of downtown Fukuoka shown by an open circle in Fig.7. For Scenario 1 the synthetic waveform is quite similar to the observed waveforms in Kobe during the Hyogo-ken Nanbu earthquake, since we assume the same rupture pattern as shown in Fig.3.



Fig. 8 Peak Ground Velocity distributions calculated for four rupture scenarios in Fukuoka



Fig.9 Synthetic velocity seismograms in downtown Fukuoka for four rupture scenarios (Fault normal component)

#### **Yatsushiro City**

In Fig.10 we show the PGA and PGV distributions for Scenario 3 of Futagawa-Hinagu fault, which is the widely distributed case shown in Fig.4. We found that we have a wide region of high PGVs along the central part of the fault. Within this high PGV region we can notice that we have a higher PGV belt close to the fault. This region is created by the edge effect of a basin structure, exactly the same cause of the damage belt in Kobe as shown in Kawase [12].

In Fig.11 we show synthetic horizontal velocity seismograms at the Yatsushiro City Hall and the Kumamoto City Hall. At Yatsushiro we have a high amplitude pulse in the beginning only in the fault



Fig.10 PGA and PGV distributions calculated for the Scenario 3 rupture model in Yatsushiro.



Fig.11 Synthetic velocity seismograms at the Yatsushiro City Hall and the Kumamoto City Hall (See Fig.10 for locations, a circle in the north: the Kumamoto City Hall)

normal component. This pulse is produced by a forward rupture directivity of two small asperities in the south of the Futagwa-Hinagu fault, as was the case in the western side of Kobe during the Hyogo-ken Nanbu earthquake. On the other hand, we have a long period pulse in Kumamoto with relatively small amplitude. This reflects the contribution of a larger asperity in the north of the fault and the propagation distance from the fault to the center of Kumamoto City.

## **BUILDING DAMAGE PREDICTION MODELS**

Based on the strong motions calculated for several rupture scenarios of dangerous inland earthquakes, we need to predict building damages to delineate the whole picture of potential disasters in the target cities. To do so we construct first numerical building models with nonlinear parameters that can reproduce the damage observed in Kobe during the Hyogo-ken Nanbu earthquake. Since we successfully reproduced strong ground motions by using Matsushima and Kawase's rupture model [3] and we successfully obtained the detailed statistics of the building damage survey conducted for Kobe, we can tune up parameters so as to reproduce observed building damage in Kobe. Details of our procedure can be found in Nagato and Kawase [4]. Here is a brief explanation of our procedure.

First we construct basic building models based on the current building design code. We assume rigid



Fig. 12 Nonlinear relationships at the basement of standard models, that is, the story drift angel versus the base shear coefficient.



Fig. 13 Relationships between yield strength factor and its existing ratio based on the probability density distribution of Shibata [15].

floors so we use a 1 column multi-degrees-of-freedom system. Fig. 12 shows nonlinear characteristics of such basic models for reinforced concrete (RC) buildings. We use degrading trilinear models here. We also need to introduce probabilistic distribution of yield strength to estimate damage probability for a given strong motion. We assume a log-normal relationship proposed by Shibata [13]. Fig.13 shows the digitized version of that log-normal distribution. We prepare for twelve models with different yield strengths. As a definition of heavy damage we use 1/30 in terms of the maximum story drift.

Once we assume initial models for different numbers of stories (3, 6, 9, and 12) and for different ages of construction (before and after 1982), then we can calibrate these models to the observed ratios of building damage (here "damage" means either "collapsed" or "heavily damaged"). We found that for RC buildings the initial models are too weak to reproduce actual damage ratios in Kobe as shown in Fig. 14. It should reflect the actual construction practice of RC buildings, namely, putting many cast-in-place walls without considering their additional strengths in the seismic design. So we increase the average yield strengths for different building categories. Fig. 15 shows final multiplication factors for RC buildings. It turns out that the average strengths of low-rise RC buildings are 2 to 4 times larger than those assumed in the ordinary design.





On the other hand, as a direct consequence of high damage ratios of steel buildings in the heavily

Fig. 14 Comparison of Calculated Damage Ratios and Observed Damage Ratios for RC buildings

Fig. 15 Multiplication factors "α" needed to reproduce Observed Damage Ratios in Kobe





Fig. 16 Observed Damage Ratios for steel buildings from the survey by Midorikawa et al. [14]



damaged areas in Kobe [14], which is shown in Fig. 16, these multiplication factors are close to 1 for low-rise steel buildings, as shown in Fig. 17. This means that steel buildings do not have any concealed yield capacities other than those considered in their seismic design.

We also construct a damage prediction model for 2-storied wooden houses by using a statistical damage data in Kobe and a trilinear plus slip spring nonlinear characteristics. Unfortunately we do not have damage ratios for different construction ages so that we have only one type of model for wooden houses.

The advantage to use these numerical prediction models for building damage is that we can automatically reflect the effects of waveforms and predominant periods of ground motions to the building damage prediction. For example, very high PGV records observed in Taiwan during the 1999 Chi-Chi earthquake did not produce so heavy damage to ordinary buildings in the observed areas and our models successfully reproduce that. If we use conventional method to predict building damage, that is, a vulnerability function based on the PGA or PGV, then predicted damage in these areas would not be reproduced.

# **RESULTS OF EARTHQUAKE DISASTER PREDICTION**

# Fukuoka City

First we will show the predicted damage distribution in Fukuoka. Fig.18 shows the damage ratio distributions for 3, 6, and 9 storied RC buildings built before 1982 and that for 12 storied RC buildings without age discrimination for Scenario 1. It is found that low-rise RC buildings show high damage ratios only in quite limited districts along the Kego fault, while middle-rise RC buildings show much wider distribution of districts with high damage ratios.

For wooden houses that occupy the largest portion of building stocks in Fukuoka, we compare damage ratio distributions for Scenario 1 to 4 in Figure 19. We found that the higher ratios are found for Scenario 1 in a wider area than for Scenario 4, although PGVs are higher for Scenario 4 as shown in Fig.8. This is so because wooden houses are more sensitive to high frequency component than low frequency one as represented by PGVs. Scenario 1 produces stronger high frequency energy in a wider area than Scenario 4. This fact shows the advantage to use our numerical nonlinear models for building damage prediction.

In Table 2 we summarize the numbers of buildings that will be collapsed or heavily damaged by four scenarios. We need to prepare for the total loss of 5 to 14% of our building stock in Fukuoka, which results in more than 30,000 buildings and houses to be damaged. We should note that Scenario 1 is the



Fig. 18 Damage ratio distribution of 3, 6, 9 storied old RC buildings and 12 storied old and new RC buildings in Fukuoka for the Scenario 1 rupture model.

most devastating in terms of total numbers of damaged buildings but that they are mainly wooden houses and for engineered structures (i.e., RC and steel) Scenario 4 is most dangerous.

# Yatsushiro City

As for the prediction for Yatsushiro City we show predicted damage distributions in Figure 20 for 3storied old (before 1982) RC buildings, 3-storied old steel buildings, and wooden houses in case of Scenario 3, the widely distributed asperity scenario. We can see almost no damage for low-rise RC buildings, while we see devastating damage for steel buildings and wooden houses in the western side of



(c) Scenario 3

(d) Scenario 4

Fig.19 Damage ratio distribution of wooden houses in Fukuoka for Scenario 1 to 4 rupture models.

type	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Old RC	365	0	34	520
New RC	75	0	8	128
Wooden	32386	1237	11057	22686
Old Steel	3675	15	1446	6397
New Steel	2098	12	746	3577
Total No.	38600	1264	13290	33307
Ratio	14.1%	0.5%	4.9%	12.2%

Table 2 Estimated numl	pers of buildings to	be damaged in ]	Fukuoka Citv
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the fault. If we look at the damage ratio distribution of steel buildings, we can see a damage belt along the Futagawa-Hinagu fault.



Fig. 20 Damage ratio distributions of 3-storied old RC buildings, 3-storied old steel buildings, and wooden houses in Yatsushiro City for the Scenario 3 rupture model

#### CONCLUSIONS

Based on strong ground motions calculated by a hybrid method and nonlinear analyses of a set of building models, we predicted the damage distributions in Fukuoka City and Yatsushiro City to delineate the whole picture of potential disasters. We found the following:

- By using a hybrid method in which we can consider both stochastic nature of high frequency component and coherent nature of low frequency component, we successfully predict near-source strong ground motions for hypothesized earthquakes in Fukuoka and Yatsushiro, Kyushu, Japan. Rupture direction is very important since it controls the area of high PGVs due to forward rupture directivity in case of strike-slip faults that we studied here.
- 2) A shallow asperity will generate a strong velocity pulse, however, high PGV does not necessarily cause heavy damage. The damage level depends on the building response characteristics, not only waveform characteristics. Therefore, it would be best to use a set of nonlinear numerical models of buildings to predict damage quantitatively for future earthquakes.
- 3) For Fukuoka City we must expect severe disaster, especially for wooden houses and row-rise steel buildings, if the Kogo fault would be broken. In two scenarios out of four we have to prepare for more than 30,000 buildings and houses to be collapsed or heavily damaged.
- 4) For Yatsushiro City the disaster will be limited to the areas close to the Futagawa-Hinagu fault. Since the residential densities are not so high in these potentially dangerous areas, total expected loss of buildings will be limited for Yatsushiro City and nearby Kumamoto City.

Since we construct purely numerical models, it is now easy to estimate what is the best way to reduce future seismic risks at earthquake prone megacities. For example, we have a huge stock of old buildings that do not conform to the current building code and it is our urgent need to promote seismic retrofitting to these buildings. We can estimate the best countermeasures for each cities with different seismic risks

based on our building models. However, it should be noted that the accuracy of the numerical damage prediction is solely depends on the reality of models parameters and so they should be calibrated to the observed data. We calibrated our models only for the Hyogo-ken Nanbu earthquake. In Japan we have more than 6,000 instruments for strong motions on the ground, but less than 1,000 instruments inside the buildings. We desperately need more building records (till collapsed) to better calibrate our building models.

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