Fault Specific, Dynamic Rupture Scenarios for Strong Ground Motion Prediction

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SUMMARY
We propose a method to estimate fault-specific, heterogeneous rupture models for scenario earthquakes incorporating dynamic rupture simulation and geological or geomorphological data. We apply our method to evaluate earthquake scenarios for the Uemachi fault system which is a 45 km-long vertical fault running underneath the Osaka plain, the southwest Japan. We define an average slip distribution whose along-strike variation is similar to that of the cumulative displacement distribution. Small-scale heterogeneity not included in the cumulative displacement distribution is added assuming fractal distribution. The slip distribution is then converted to static stress drop distribution and incorporated into the dynamic rupture simulation. Resultant earthquake scenarios show unsmooth rupture propagation leaving unruptured parts on the fault plane reflecting the heterogeneity of the stress field. The rupture spontaneously stops near the bottom of the fault plane, which successfully demonstrates the die-out of the high-speed rupture near the bottom of the seismogenic zone.

Keywords: earthquake scenario, dynamic rupture simulation, active fault, slip rate, ground motion prediction

1. INTRODUCTION

What size of asperities (patches with relatively large slip), where to locate them, and how to set the rupture propagation on them are the most important subjects in modelling a hypothetical earthquake source for ground motion prediction. As former studies have shown, strong ground motions and resultant damages are often characterized by microscopic features of source process, especially ruptures of asperities.

There are two general ideas about the variation of slip due to earthquakes repeatedly occurring on an active fault; characteristic earthquake model and variable slip model (Schwaltz and Coppersmith, 1984). In the former model, a fault ruptures with a same slip distribution. In the latter model, the slip distribution varies from earthquake to earthquake. Lindvall et al. (1989) and Sieh and Jahns (1984) have shown that displacement distributions on surface ruptures are always similar, which supports the former model. Though, there are few observations on the spatial and temporal characteristics of fault ruptures over multiple seismic cycles.

We have an idea not exact but closer to characteristic earthquake model. It is reasonable to assume that there is a rather stable, average stress distribution on an active fault over some geological time scale (10e+6 yrs) when roughly-constant tectonic stress is acting on a stable crustal structure and that therefore, there are some patterns in slip distributions of repeated earthquakes. If it is so, the average stress distribution can be evaluated from the distribution of the cumulative displacement.

The Uemachi fault system, the target active fault in this study, is a reverse fault running N-S direction just underneath the Osaka plain, the southwest Japan. The history of its fault ruptures since millions of years ago is marked in the sedimentary structure. The spatial distribution of the fault slip rate (the cumulative displacement of a layer divided by its sedimentary age) shows a peak with the highest rate in the northern part of the fault, low rate in the middle part, and another peak in the southern part. The slip rate and its spatial distribution are rather stable even though the key layer to evaluate the slip rate is varied, which assures the long-term stability of the stress distribution on this fault system.

If the stress distribution is estimated, we can simulate the rupture propagation by solving the dynamics on the fault surface. There are uncertainties in the dynamic simulation of the fault rupture due to uncertainty of the dynamic parameters, e.g. friction coefficients. But still, we can expect that the stress distribution and dynamic consideration will predict a plausible feature of the specific situation.

In this paper, we propose a method to estimate fault-specific, heterogeneous rupture models for scenario earthquakes from distributions of cumulative displacement measured along active faults. We define an average earthquake slip distribution whose along fault strike is similar to the cumulative displacement distribution on the active fault. The slip distribution is then converted to static stress drop distribution and incorporated into the dynamic rupture simulation. Spontaneous rupture propagation on the fault plane is simulated by the finite difference method assuming slip-weakening friction law on the fault plane.

We have developed methodologies under essentially the same idea as above (Kase et al., 2003; Sekiguchi et al., 2003; Sekiguchi et al., 2005). This study revise the previous one about the free-surface condition for the fault rupture reaching the surface in the finite difference method and the small-scale heterogeneity of slip and stress drop.

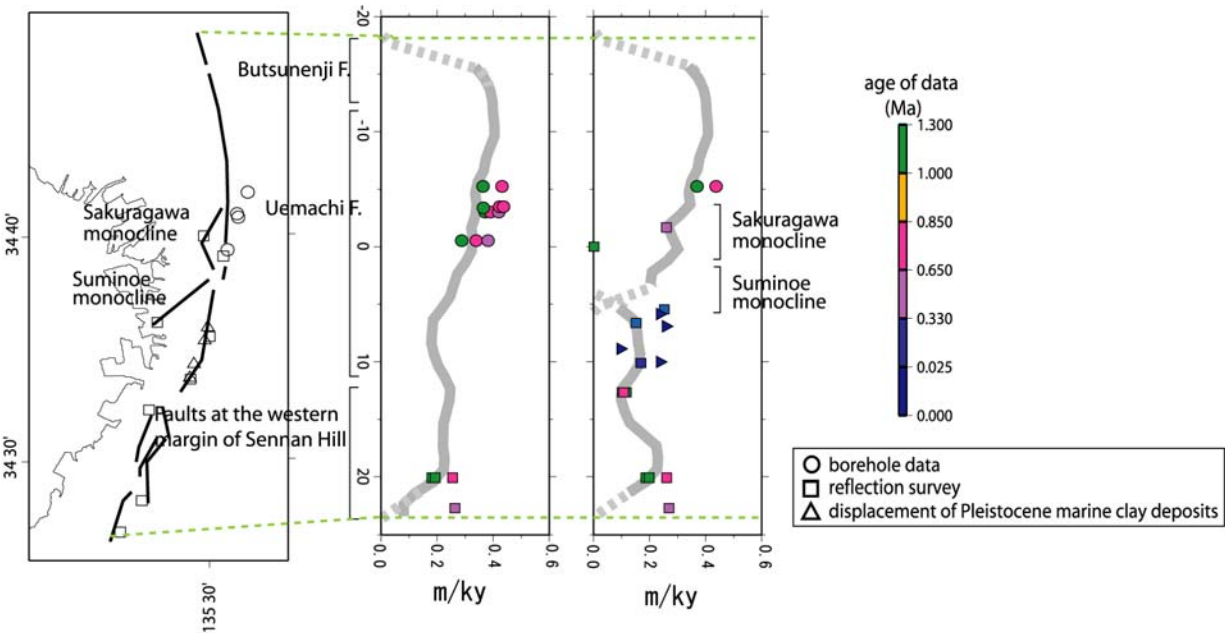

Figure 1. Spatial variation of the average slip rate (uplift component) deduced from difference of depth of Ma3 layer of the 3D sedimental structure model (Horikawa et al., 2003) (gray line) with those deduced from boring, seismic reflection survey and vertical offsets of terrace surfaces (circles, rectangles, and triangles) (Sekiguchi et al., 2003)

2. METHOD AND RESULTANT EARTHQUAKE SCENARIOS

To obtain physically plausible earthquake scenarios for a specific fault, we first model the fault geometry and the stress distribution on the fault plane based on geological and geomorphological data, then, we calculate dynamic rupture processes on the fault under this condition.

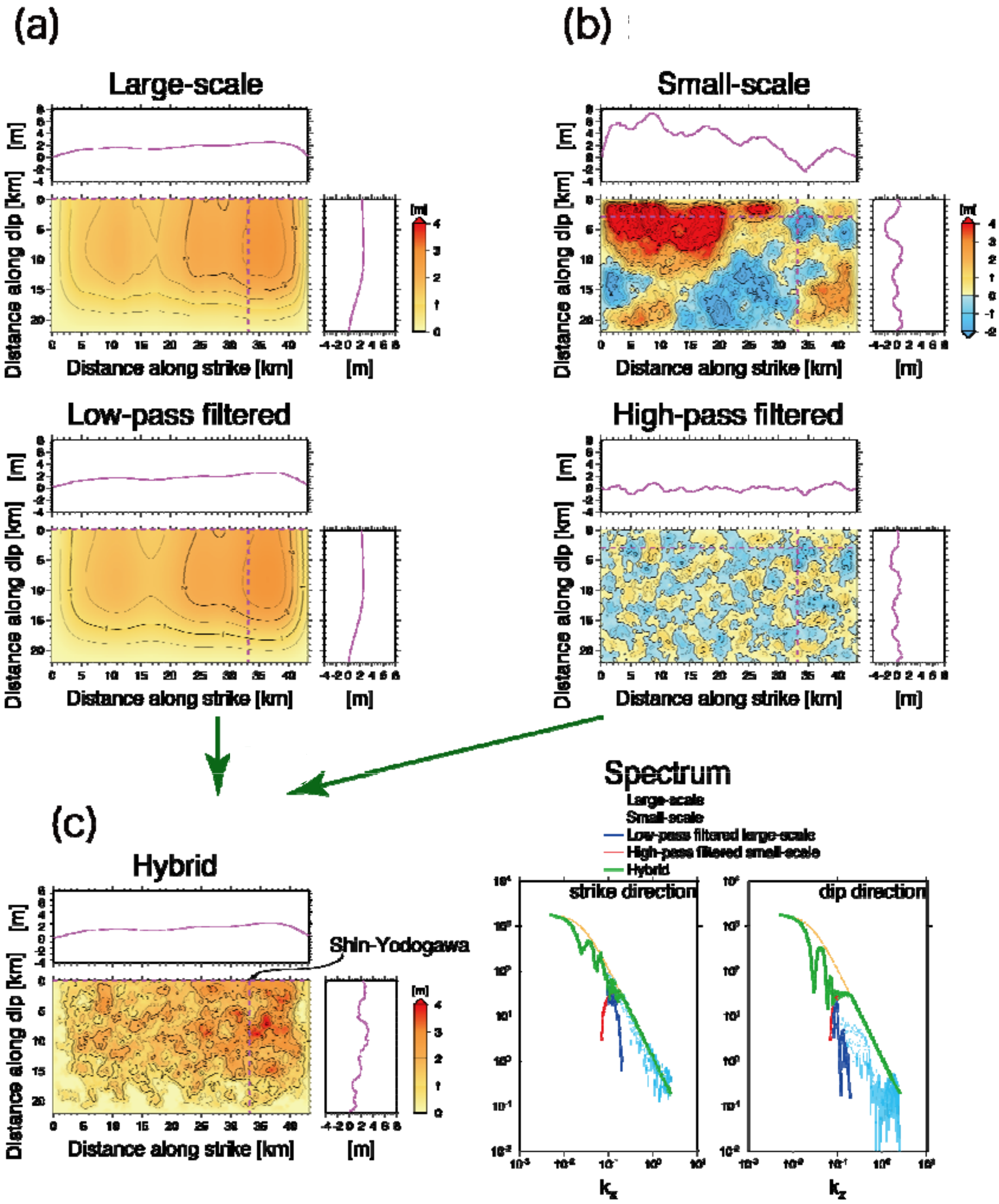

Figure 2. Process to construct an average slip distribution. (a) Average slip distribution presumed from geological and geomorphological data and preliminary dynamic rupture simulations (upper) and its low-pass filtered distribution (lower). (b) Fractal heterogeneity of slip (upper) and its high-pass filtered distribution (lower). (c) Presumed slip distribution model with a wide-scale slip distribution.

2.1. Fault Plane Model

A curved fault plane model was constructed by extending 60 degrees-dipping surface from the surface trace of the fault as done in Sekiguchi et al. (2005). The dip angle was given based on reflection surveys.

2.2. From Slip Rate to Average Slip Distribution Model

The stress condition is presumed based on slip distributions on the fault. Spatially varied cumulative slip distribution along the strike of the Uemachi fault system was obtained by reflection surveys, borehole data, etc. The borehole data at Shinyodogawa along the fault showed that the vertical slip on the earth's surface due to the last event was between 1.6 and 1.9 m and possibly 2.4 m at largest (Sugiyama et al., 2003). Combining these data, we presume an average slip distribution along strike.

The along-dip slip distribution is modelled through simulations of spontaneous ruptures under depth-dependent stress conditions to realize spontaneously stopping rupture near the bottom of the seismogenic zone. At this step, the regional stress field and dynamic coefficient of friction on the fault plane that realize the vertical slip due to the last event are searched under the condition characteristic of the tectonic stress in this region; i.e., principal stresses proportional to depth, E-W directed maximum principal stress, and minimal principal stress in vertical.

Combining the along-strike and along-dip distributions, we get a large-scale heterogeneous slip distribution model (Fig. 2a). Finally, we add short-scale, fractal heterogeneity (Fig. 2b) onto this large-scale heterogeneous slip distribution model to obtain a wide-scaleslip distribution (Fig. 2c).

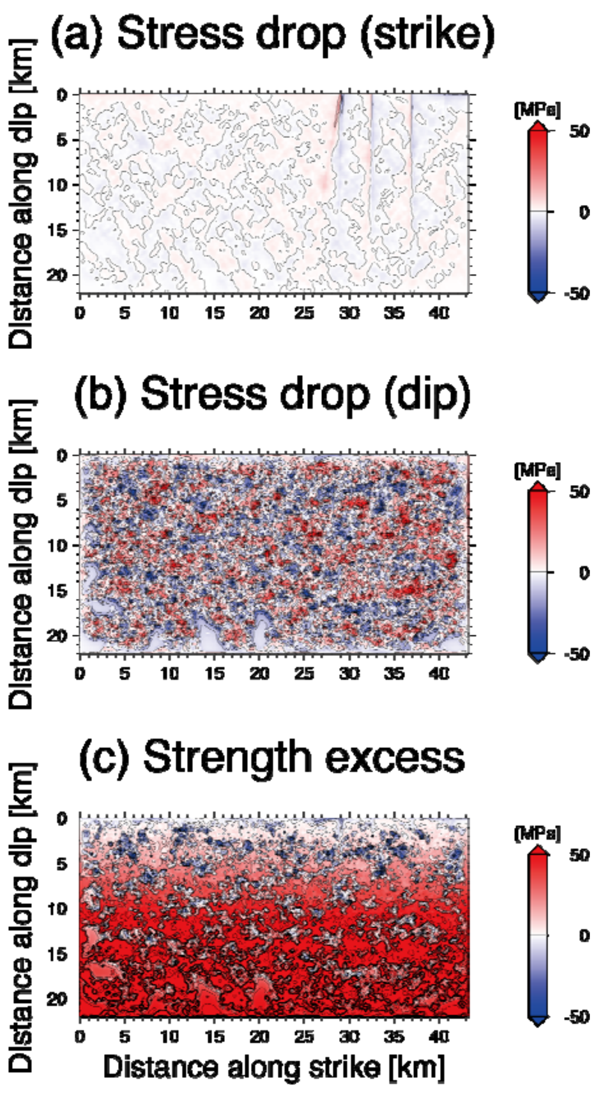

Figure 3. Stress condition on the fault plane.

2.3. Dynamic Parameter on the Fault Plane

The slip distribution is converted to the distribution of static stress drop (Figs. 3a and b) using the method by Okada (1992). Assuming that the heterogeneities of the principle stresses cause the heterogeneity of the stress drop, the heterogeneous normal stress distribution is calculated. Therefore, the heterogeneous strength distribution is calculated by multiplying static coefficient of friction to the heterogeneous normal stress distribution.

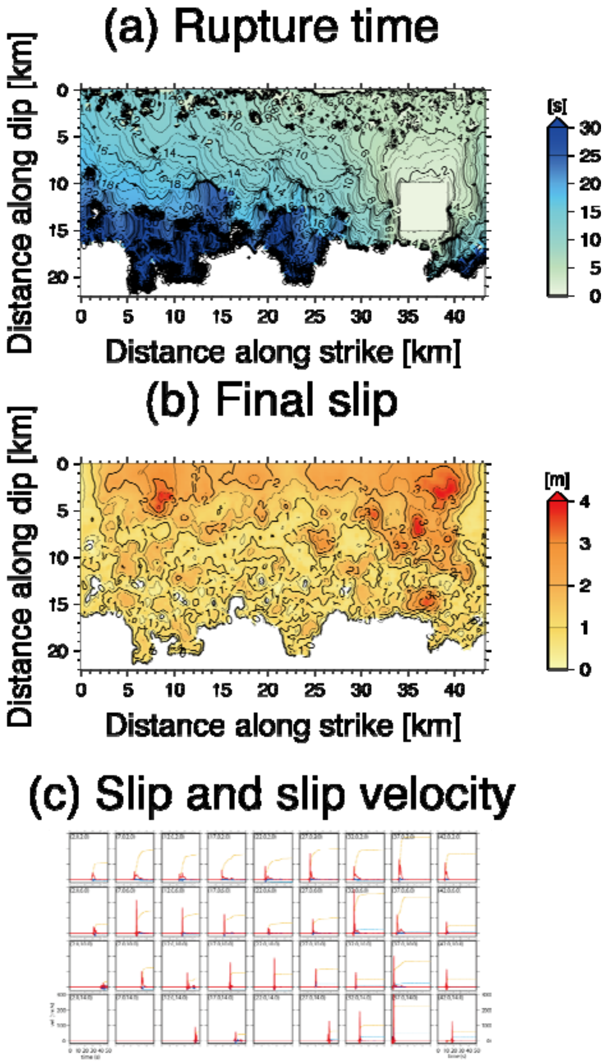

Figure 4. Rupture propagation (a), final slip (b), and slip time histories on the fault (c) of an earthquake scenario.

2.4. Dynamic Rupture Simulation and Earthquake Scenario

We calculate dynamic rupture processes by the finite-difference method (Kase, 2010). The boundary conditions on the fault plane are Coulomb's rupture criterion and slip-weakening friction law. For each stress drop model, some hypocenter locations are assumed.

Rupture area and rupture time on each point depend on stress model and hypocenter location. Fig. 4 shows the dynamic rupture process of a scenario with its hypocenter assumed at 6.5 km in along-strike direction from the northern end and 12.5 km in along-dip direction from the top of the fault plane (10.8 km deep). The total seismic moment of the scenario earthquake is 3.5×10^{19} Nm (Mw7.0). Due to the heterogeneity of the stress field, the rupture does not propagate smoothly and some areas remain unruptured (Fig. 4a). The local rupture velocities in most of the large slip areas are 2.5 to 3.0 km/s. The rupture in the area shallower than 5 km tends to precede those in the deeper part, which is interpreted by the low strength on the shallow part of the fault plain.

Final slip distribution (Fig. 4b) recovers the presumed slip distribution (Fig. 2c) fairly well. The rupture spontaneously stops in the area near the bottom of the fault plane ranging 15 to 22 km in along-dip direction from the top of the fault plain (13 to 19 km deep), which successfully demonstrates the die-out of the high-speed rupture near the bottom of the seismogenic zone. The slip velocities on the fault plane have impulsive narrow peaks (Fig. 4c) reflecting the strong heterogeneity of the rupture time and the slip distributions.

3. GROUND MOTION

We computed the ground motion due to this earthquake scenario up to 1 Hz using the finite difference method (Pitarka, 1999). The subsurface structure is modelled combining the 3D Osaka sedimentary basin model (Fig.5a; Horikawa et al., 2003) and 1D crustal structure model (Maeda and Watanabe, 1984). Largest strong motions are distributed near the northern part of the Uemachi fault, which is caused by the forward directivity pulse due to the upward directed rupture propagation from the hypocenter, strongly amplified by the sediments of the basin (Fig. 5b).

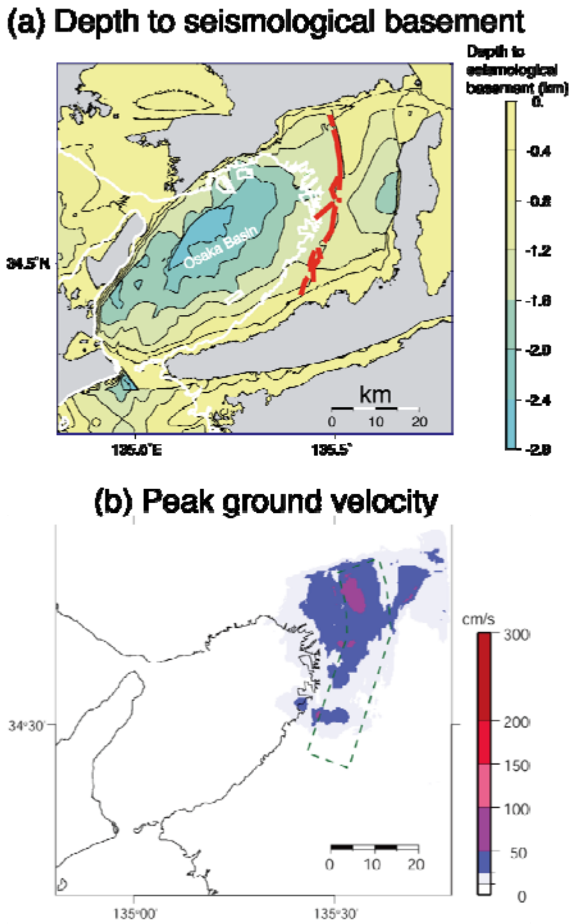

Figure 5. Sediment thickness distribution (a) and ground motion distribution due to the earthquake scenario shown in Fig. 4 (b).

4. CONCLUSIONS

We propose a method to estimate earthquake scenarios with heterogeneous slip distribution and rupture propagation incorporating rupture dynamics and fault specific stress field derived from the history of fault activity. Intensive studies of the Uemachi fault system using geophysical, geological and geomorphological technique are under way (Iwata et al., 2012). Our model may be revised reflecting the new information.

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