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CHARACTERIZATION OF DYNAMIC ASPERITY SOURCE MODELS FOR SIMULATING STRONG GROUND MOTION

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SUMMARY

Asperity source models are important since recent studies have clarified that the main contribution to strong ground motion comes from the asperity area. These models are defined by the fault parameters: fault area, average slip, maximum slip, peak slip velocity, and stress drop both of the overall fault and asperity area. The ratios of these parameters between the asperity and the total rupture area, together with the scaling relations of fault models, make feasible the definition of the asperity source model. Since dynamic rupture models take into account the physical conditions of the friction and stress distribution across the fault, we estimated the ratios between the above parameters from dynamic models capturing more realistic seismic source properties. We started assuming that the combined asperity area is 0.22 times the total rupture area as following the slip characterization for kinematic models of Somerville et al. [1]. Sub-surface earthquakes, represented as circular faults, and surface earthquakes, represented as rectangular faults that break the free-surface, are simulated for single and multiple asperities. We assumed different conditions of stress drop surrounding the asperity (background area) that vary from –0.2 to 0.2 times the stress drop of the asperity area. A fixed rupture velocity (0.8 of S-wave velocity) and the simple slip-weakening friction model on the fault were used for the dynamic rupture propagation. The dynamic rupture simulation suggests that the characterized source model of Somerville et al. [1] is valid when the ratios of stress drop between the background and asperity is between –0.05 to 0.1 for sub-surface earthquakes and between –0.15 to 0.05 for surface earthquakes. We also found that the average peak slip velocity in the background area with zero stress drop is around 0.3 times the one in the asperity area. These characterized parameters verified by dynamic faulting are playing an important role for practical application of strong ground motion prediction.

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INTRODUCTION

The source model for strong ground motion prediction and earthquake scenario is usually developed from scaling relations of characterized source models developed by kinematic approach (e.g. Somerville et al. [1]). Since the origin of these scaling relations comes from kinematic approach, they do not take into account the physical causes of the earthquakes, that is, the stress that causes or participates in the source process is neglected. The target of this paper is to fill this gap and complement these models using dynamic approach. We attempt to investigate the physical causes and under which conditions the kinematic source characterized source models are valid.

The recent studies developed by Miyake et al. [2] have clarified that the main contribution to high and low frequency strong ground motion comes from the asperity area. The asperity models, as well as the barrier models, are widely used for representation of the fault-zone heterogeneity, in which both terms are related to the stress and strength distribution along the fault plane. The classical definition of these models (e.g., Kanamori and Stewart [3], Aki [4]) is a simple as well as robust description of such heterogeneity. From the definition that the seismic radiation and the slip on the fault are produced by the stress drop and, that the asperity areas is the main responsible for generating the strong ground motion during earthquakes, asperity area can be defined as the zone with the high stress drop. Therefore, the identification and characterization of asperity models play an important role for practical application of strong ground motion prediction and ground motion simulation for engineering purpose. From classical circular single-asperity source model studied by Madariaga [5], Das and Kostrov [6] and Boatwright [7] it is possible to approximately derive the relationship between the stress drop on the asperity ($\Delta\sigma_a$), the total seismic moment (Mo), the combined asperity area and total rupture area as follow:

$$\Delta\sigma_a = \frac{7}{16}\frac{M_0}{Rr^2} \tag{1}$$

where *R* and *r* are the radii of the circular fault and circular asperity respectively. And It is assumed for an arbitrary position of the asperity area.

But this relation is limited to only one asperity with zero stress drop out of the asperity area. Furthermore, this expression may be accepted only for self-similar sub-surface earthquakes. Since earthquakes are the results of dynamic rupture process in which the friction and stress distribution across the fault are taking in to account, and they can be surface or sub-surface earthquakes, the dynamic analysis of the asperity-source model certainly provides more realistic seismic source properties. Therefore, we developed dynamic rupture simulations for single and multiple asperity-source models for surface and sub-surface earthquakes, and from the results we propose the ratios of the fault parameters (fault area, average slip, maximum slip, peak slip-velocity, and stress drop) between the asperity and the total rupture area. The sub-surface earthquakes are simulated by means of circulars faults, and the surface earthquakes by rectangular faults in which the faulting breaks the free-surface. The ratios obtained with these dynamic rupture simulations together with the scaling relations of fault models (e.g. Somerville et al. [1]) make feasible the definition of the asperity source model for ground motion simulation.

CIRCULAR ASPERITY MODELS (SUB-SURFACE EARTHQUAKES)

We performed 3D simulations of dynamic faulting for a series of single and multiple circular asperity-source models (Figure 1) using the staggered-grid finite-difference code of Pitarka [8]. The problem is tackled assuming that the fault is embedded in an unbounded medium with no free surface. Then the simulated earthquakes would be considered as self-similar in which the ratios obtained from the slip, slip velocity, and stress drop remain invariant with the size of the fault. The ratio between the combined asperity area and total rupture area is equal to 0.22 for all the models. This ratio, proposed by Somerville et al. [1] fits the characteristic slip models of recent large earthquakes. The size of total rupture area is S= 400km^2, size of combined-asperity area S_a=88km^2, stress drop for asperities $\Delta\sigma_a=10.5$MPa, stress drop for background area $\Delta\sigma_b$=-0.20, 0.0, 0.10, 0.15 and 0.20$\Delta\sigma_a$, rigidity μ=3.0GPa, S-wave velocity V_s =3.2km/s, density ρ=2.8gr/cm^3. The dynamic rupture propagation is developed assuming a fixed rupture velocity (0.8 of S-wave velocity) and the simple slip-weakening friction model in the form given by Andrews [9] with a critical slip-weakening distance D_c=0.4m is used. This friction law that was first proposed by Ida [10] is extensively used for dynamic simulation of fault rupture process (e.g., Andrews, [9]; Day, [11]; Olsen et al., [12]; Fukuyama and Madariaga, [13]; Harris and Day, [14], Dalguer et al., [15] and supported by laboratory experiments (e.g. Ohnaka *et al*., [16]; Ohnaka and Shen [17] these authors conclude that their experiments could be explained with a simple slip weakening friction law model.

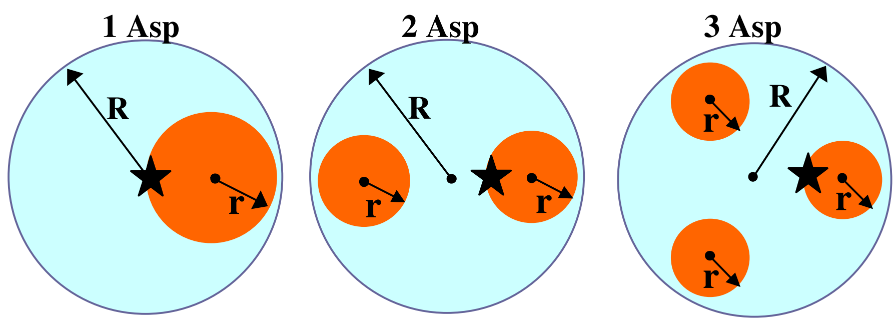

Figure 1. Circular asperity models for dynamic rupture simulation of sub-surface earthquakes. *R* and *r* are the radii of the circular fault and circular asperity respectively. The star represents the hypocenter.

Figure 2 shows the ratios of average slip and maximum slip for the circular asperity models of Figure 1. The gray arrow represents the band in which the characterized kinematic slip model proposed by Somerville et al. [1] is equivalent to the dynamic model. From this figure we can conclude that the kinematic scaling models fit the dynamic models when the ratios of stress drop is in the band of $-0.05 < \Delta\sigma_b/\Delta\sigma_a < 0.10$. Corresponding $\Delta\sigma_b/\Delta\sigma_a \approx -0.05$ for triple, $\Delta\sigma_b/\Delta\sigma_a \approx 0.0$ for double and $\Delta\sigma_b/\Delta\sigma_a \approx 0.1$ for single asperity models. These figures also suggest that the number of asperities decreases the ratios. A more detail analysis and more general cases of circular asperity models are studied in our paper in preparation (Miyake et al [18]).

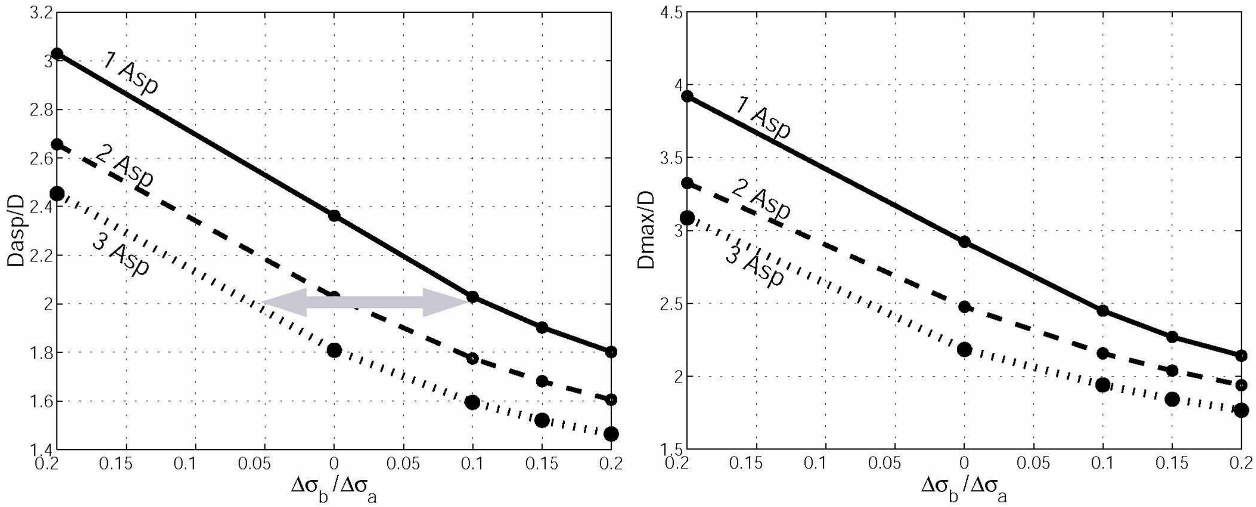

Figure 2. Average slip ratio (Dasp/D) and maximum slip ratio (Dmax/D) plotted with the stress drop ratio ($\Delta\sigma_b /\Delta\sigma_a$) for the dynamic solution of the asperity models shown in Figure 1. The arrow specifies the band of the stress drop ratios in which fit the characterized slip model proposed by Somerville et al. [1].

The peak slip-velocity ratio between the back ground area and the asperity area is also estimated from the dynamic rupture models. For this calculation we used a single asperity model with the asperity located at the center of the fault. Figure 3 shows these results as a function of the stress drop ratio. The average peak slip-velocity in the background area with zero stress drop is around 0.3 times the one in the asperity area. As the stress drop ratios increase, the ratios of peak slip-velocity increase.

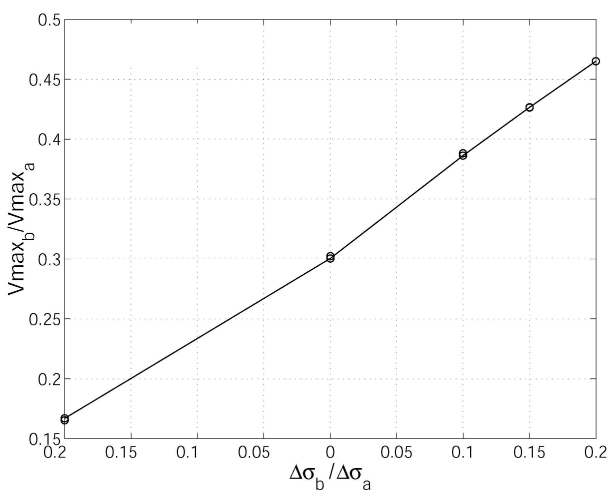

Figure 3. Relationship between the ratio of maximum slip-velocity ($Vmax_b$ /$Vmax_a$) with stress-drop ratio ($\Delta\sigma_b /\Delta\sigma_a$) for the dynamic solution of a circular single asperity model with the asperity located at the center of the fault. The $Vmax_a$ and $Vmax_b$ are the average of maximum slip-velocity in the asperity area and in the back ground area, respectively.

RECTANGULAR ASPERITY MODELS (SURFACE EARTHQUAKES)

Larger earthquakes are expected not to be self-similar anymore, then, the ratios for circular asperity models estimated above my fail for this kind of earthquakes. In order to verify it, we developed a series of rectangular asperity models assuming that the faulting breaks the free-surface. This kind of earthquake we can categorize as surface fault. Our simulations consist of earthquakes with $L>=W_{max}$, where L and W are the length and width of the fault, respectively. W_{max} is assuming to be 20km that represents the brittle crust of the earth. The fault models are calculated up to $L<=20W_{max}$. The ratio between the combined asperity area and total rupture area is equal to 0.22 as also used for the circular asperity models. The number of asperities increases with L, as shown in Figure 4, assuming single asperity for L=W=20km, double for L=40km, triple for L=100km, and quadruple for L>=200km. The material properties and friction law are the same as for the circular asperity models.

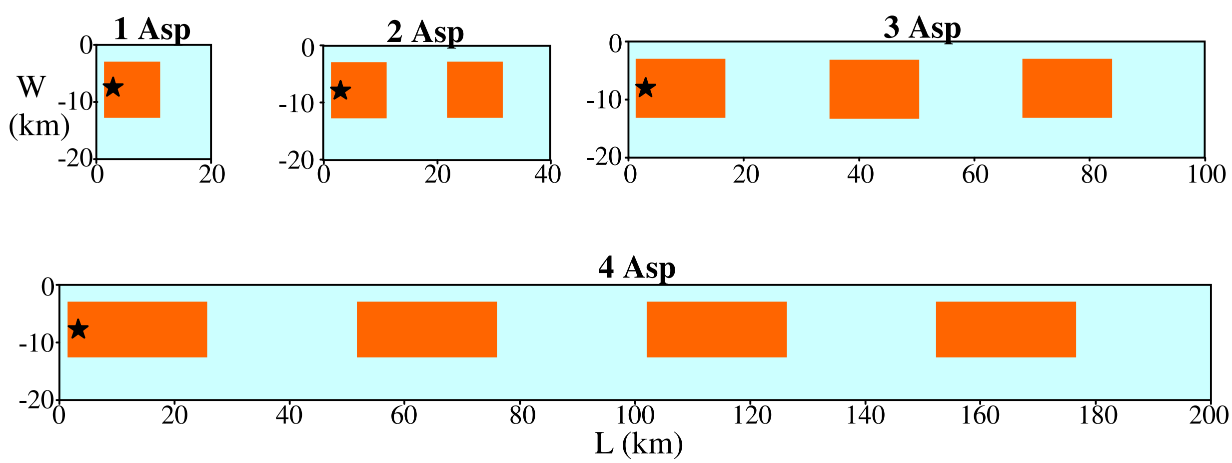

Figure 4. Rectangular asperity models for dynamic rupture simulation of surface earthquakes. Single asperity model is for L=W=20km, double for L=40km, triple for L=100km, and quadruple for L>=200km. L and W are the length and width of the fault, respectively. The star represents the hypocenter. The zero level is the free-surface.

Figure 5 shows the ratios of average slip and maximum slip for the rectangular asperity models of surface earthquakes. The gray arrow represents the band in which the characterized kinematic slip model proposed by Somerville et al. [1] is equivalent to the dynamic model. For this kind of earthquakes the ratios decrease when compared with the ratios of circular asperity models. The band of stress drop ratio that fits the kinematic scaling model is now $-0.15 < \Delta\sigma_b/\Delta\sigma_a < 0.05$. This decrease of ratio is expected because the average slip (D) increases due to the free-surface effect. It is interesting to observe that the ratios for models with 3 and 4 asperities are almost the same. It is because the tendency of saturation of not only the average displacement when L increases, but the average displacement of the asperity tends to saturate as well. Therefore the ratio of average slip between the asperity and total rupture area also saturates. The results suggest that fault with more than two asperities remain the same ratio for surface earthquakes with $L>4W_{max}$

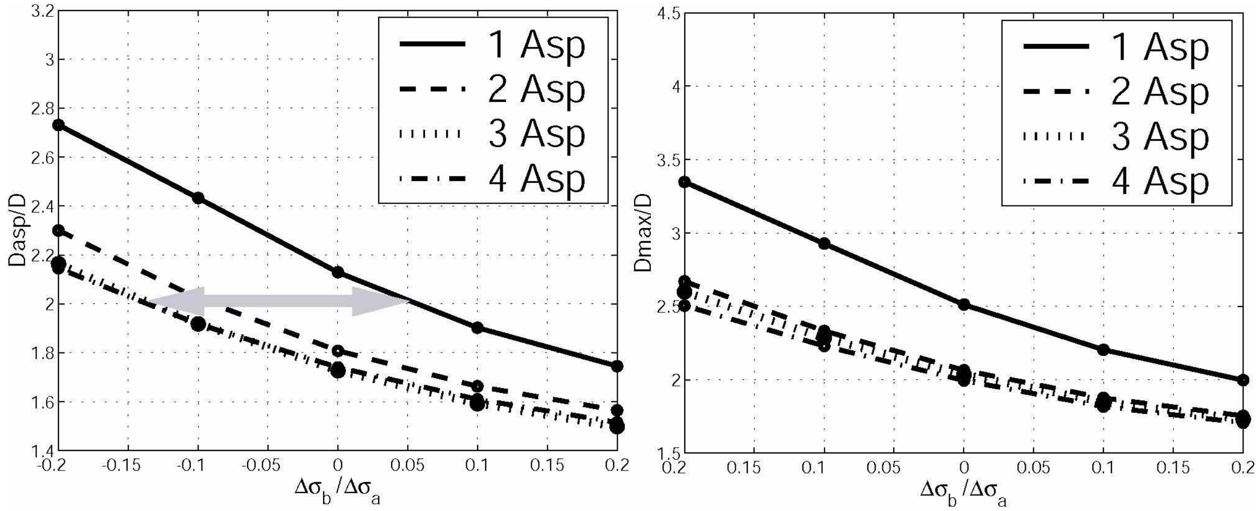

Figure 5. Average slip ratio (Dasp/D) and maximum slip ratio (Dmax/D) plotted with the stress drop ratio ($\Delta\sigma_b$ /$\Delta\sigma_a$) for the dynamic solution of the rectangular asperity models of surface earthquakes in which the number of asperities increases with L, assuming single asperity for L=W=20km, double for L=40km, triple for L=100km, and quadruple for L>=200km. The arrow specifies the band of the stress drop ratios in which fit the characterized slip model proposed by Somerville et al. [1].

CONCLUSIONS

We proposed scaling ratios calculated by dynamic models for single and multiple asperity models for sub-surface earthquakes (circular faults) and surface earthquakes (rectangular faults that reach the free surface) with different conditions of stress drop distribution along the fault. The size of the combined asperity was fixed as 22% of the total rupture area, following the study of Somerville et al. [1]. From the viewpoint of dynamic faulting, our finding indicates that the characterized source model of Somerville et al. [1] is valid when the ratios of stress drop between the background and asperity is between –0.05 to 0.1 for sub-surface earthquakes and between –0.15 to 0.05 for surface earthquakes. The characterized ratios for slip and stress drop make feasible the definition of asperity-source models for practical application of strong ground motion prediction, accompanying with the source scaling relation of sub-surface to surface earthquakes.

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