

RUPTURE MODELS AND GROUND MOTION FOR SHAKEOUT AND OTHER SOUTHERN SAN ANDREAS FAULT SCENARIOS

L.A. Dalguer¹, S.M. Day², K. Olsen³, and V.M. Cruz-Atienza⁴

¹ *Institute of Geophysics, ETH-Zurich, Switzerland*

² *Dept. of Department of Geological Sciences, San Diego State University, San Diego, USA*

³ *Dept. of Department of Geological Sciences, San Diego State University, San Diego, USA*

⁴ *Dept. de Sismología, Universidad Nacional Autónoma de México, Mexico*

Email: dalguer@tomo.ig.erdw.ethz.ch, day@moho.sdsu.edu, kbolsen@sciences.sdsu.edu,
cruz@geofisica.unam.mx

ABSTRACT :

The SoSAFE (Southern San Andreas Fault Evaluation) ShakeOut scenario has been considered as potential strong earthquake (Mw 7.81±0.06) expected from the southern San Andreas fault. This scenario defines a rupture that initiates near Bombay Beach and propagates unilaterally 300 km toward the northwest. An essential feature of the source description of the ShakeOut scenario is the final slip profile along the strike of the fault defined from geological observations.

We performed three sets of large-scale dynamic rupture simulations that have stochastic irregularities compatible with seismological observations and match the ShakeOut Mw. The sets of models are differentiated between them in the slip distribution characteristics as follow: The first set of models match the ShakeOut final slip profile defined as surface slip, the second set matches the final slip profile defined as depth-averaged slip, and the third set of models does not follow any ShakeOut slip profile, rather it is result of the purely stochastic input parameterization. In addition, we performed a fourth model, defined as asperity model, consistent with the calibrated dynamic rupture models proposed by Dalguer at al., 2008, BSSA. The first two sets of models are strictly ShakeOut Scenarios, as defined by The SoSAFE group, and the last two are not.

Beside the wide variety of complex rupture and near source ground motion patterns between the models, the ground motion characteristics on critical areas such as Los Angeles basin are different between the ShakeOut and no-ShakeOut scenarios. The ShakeOut Scenarios predict lower ground motion than the no-ShakeOut Scenarios.

KEYWORDS: Rupture dynamic, large-scale earthquakes, SoSAFE ShakeOut scenarios, strong ground motion, numerical modeling

1. INTRODUCTION

Southern California Earthquake (SCEC) scientists have defined the SoSAFE (Southern San Andreas Fault Evaluation) ShakeOut scenario as potential strong earthquake ($M_w 7.81 \pm 0.06$) expected from the southern San Andreas fault (Hudnut et al, 2007a,b). The source description of this scenario has been well constrained with geologic, geodetic and paleo-seismic observation. This description defines the earthquake rupture scenario to initiate near Bombay Beach and propagates unilaterally 300 km toward the northwest up to near Lake Hughes (Figure 1). In addition to the rupture length, the ShakeOut scenario has the characteristic of surface rupture with a final slip profile (or “background” slip distribution model as named by the ShakeOut team) along strike of the fault. This final slip profile was constructed from geological observation in the San Andreas fault, as well as paleoseismic evidence for the date of the most recent earthquake and a time-predictable model of earthquake recurrence (Shimazaki and Nakata, 1980). This scenario is currently under evaluation and study by earthquake scientist of SCEC in order to quantify and predict strong ground motion caused by this event in Southern California, for seismic hazard and seismic risk assessment.



Figure 1. Map of the southern California where Los Angeles, San Diego and Palm Spring cities are indicated by the arrows. The 300km white line approximately represents the simplified planar fault of San Andreas fault used for our numerical simulation. The black line under the with line is the actual fault trace geometry. The start represents the epicenter of the rupture (near Bombay Beach) that propagates unilaterally toward the northwest up to near Lake Hughes.

Numerical simulations of a large earthquake rupture ($M_w 7.7$) in southern San Andreas fault have been developed using both kinematic (Olsen et al, 2006) and dynamic models (Olsen et al 2008a). These studies have enormous contribution to the understanding of different aspects related to earthquakes mechanism and near source ground motion in this area. The kinematic model, for example, has revealed that mechanism of energy channeling and focusing by sedimentary waveguides can considerably magnify the ground motion in Los Angeles area basin. This mechanism turns to be important if the directivity effect is developed strongly. The dynamic model of Olsen et al., 2008a shows that directivity effect is reduced due to incoherence of rupture propagation, then the ground motion in Los Angeles area is not as high as estimated from kinematic source models. Kinematic (Aagard et al., 2007) and dynamic (Dalguer et al., 2007) source models for the ShakeOut scenarios have been also used to predict ground motion distribution in southern California (Olsen et al., 2008b, Graves et al., 2008, Bielak et al., 2008). The ground motions resulted from these sets of models are qualitatively consistent with the results of Olsen et al (2008a), in the sense that directivity effect is also reduced in the dynamic models due to incoherence of rupture propagation. Therefore ground motion resulted from dynamic models is lower than the one predicted from kinematic models in areas such as Los Angeles basin.

Here we perform a diversity of dynamic rupture models in the southern San Andreas fault. One type of models obeys the ShakeOut Scenarios description, while the other type of models not. When compared the ground motion generated by these two types of models, we found that models that follow the ShakeOut source description predict lower ground motion than the models with no-Shakeout description in critical areas such as Los Angel basin.

The ground motion pattern results presented in this paper are merely qualitative, because 1) The ground motions are simulated from a dynamic planar fault model (see Figure 1); 2) these dynamic planar fault models are the first step of a two step procedure to estimate ground motion for the ShakeOut scenario (Olsen et al, 2008), in which for this first step, a 3D velocity model was constructed from the SCEC community velocity model (CMV) version 3, by mapping the CVM (that contents an actual non-planar fault geometry) to a planar fault configuration; and 3) this altered 3D

velocity model may generate a quantitative bias in the ground motion estimated from the dynamic rupture simulation, but the effects on the qualitative macro-scale features are minor, since the mapping procedure to move from the actual fault geometry to a planar fault is not so radical (as seen in Figure 1).

2. DYNAMIC RUPTURE MODELS

We build three sets of dynamic rupture models in a simplified planar fault (as described in the previous section) that have stochastic irregularities compatible with seismological observations reported by Mai and Beroza (2000). And a fourth asperity model consistent with the dynamic asperity model proposed by Dalguer et al. (2004) and Dalguer et al. (2008). The sets of models matches the ShakeOut moment magnitude $M_w = 7.81 \pm 0.06$, and ruptures the full length (300km) of the specified scenario. The difference between these sets of models is in the final slip distribution as follow: The first set of models matches the ShakeOut final slip profile defined as surface slip, the second set matches the final slip profile defined as depth-averaged slip, the third set of models does not follow any ShakeOut slip profile, rather it is result of the purely stochastic input parameterization, and the fourth model is an asperity model with patches of high stress drop coherently distributed along the strike of the fault. This asperity model is characterized by a large area of negative stress drop surrounding the asperities and obeys source scaling of averaged stress drop and final slip distribution consisted with statistical observation of past earthquakes (Dalguer et al 2008). The first two sets of models are strictly ShakeOut scenarios and the last two not.

We use the staggered-grid split node (SGSN) method, for dynamic rupture simulation of planar faults, recently developed by Dalguer and Day (2007). The SGSN method has well-verified accuracy and efficiency and it was implemented in the Message Passing Interface (MPI) Finite Difference code of the TeraShake platform (Olsen et al., 2006), which is scalable to thousands of processors, enabling high-performance execution for large-scale dynamic rupture models (Dalguer et al, 2006). For the stochastic models we use the “slip-matching” technique developed by Dalguer et al., (2007) for constraining stress drop conditions in simulations such that they conform to slip scenarios defined a priori. The slip-matching method iteratively performs kinematic and dynamic simulations to find both stress drop and strength excess (relative strength to rupture) distributions that (i) have stochastic irregularities compatible with seismological observations, (ii) are slip-matched to either surface slip or depth-averaged slip scenarios or simple the seismic moment, and (iv) rupture the full length of the specified scenario with predominately sub-shear rupture speed. The later is not fully satisfied by all the models. Due to intrinsic inner rupture complexities of dynamic rupture approach, some models either do not rupture the full length or propagate partially or totally with super-shear speed. Source models were derived from stochastic slip distributions using Gaussian (G) and Von Karman (VK) correlation functions (Mai and Beroza, 2000).

Figure 2 shows the stress drop distribution from six dynamic models. Zero or negative stress drop at the first 2km depth are set as near free-surface constraint. Model named g3d7, g4d4 and v1d3 are ShakeOut scenarios designed to match the ShakeOut final slip profile defined as surface slip (Dalguer et al 2007); model named g6d3_dav is a ShakeOut scenario designed to match the ShakeOut final slip profile defined as depth-averaged slip; model g7d2_M0 is a no-ShakeOut scenario designed to match the seismic moments scenario only, in which final slip is result from the purely stochastic distribution input; and the model named “asperity model” is also a no-ShakeOut scenario parameterized following the calibrated asperity model of Dalguer et al (2004) and Dalguer et al., (2008), These authors calibrated the stress drop distribution (that results in fault ruptures consistent with statistical observations of past earthquakes) and inferred that the surface-rupturing earthquakes are characterized by a large area of negative stress drop surrounding the asperities, while buried earthquakes are characterized by no-negative stress drop. So, our asperity model for the San Andreas fault lies on the surface-rupturing earthquake class.

3. FAULT RUPTURE SOLUTIONS

The solution to the dynamic rupture of our series of models results in a wide variety of complex rupture patterns, all reproduce the target moment magnitude ($M_w 7.81 \pm 0.06$). The solution between the models varies greatly in their fault-plane distributions of final slip, peak slip rate, dynamic stress drop and rupture time front. Even though this variability between the models, averages are nearly identical as shown in Table 1. Figure 3 and 4 shows respectively the final slip and peak slip rate distribution. The ShakeOut scenario models closely reproduce their respective final slip profile scenario. These ShakeOut scenario models have in common two well defined patches of large slip and peak slip rate at the extremes of the fault, one patch located on the first 100km segment from the hypocenter, and a second patch on the last 100km segment at the end of the fault. However, the patches of large slip from the no-ShakeOut scenario g7d2_M0 model are distributed over the fault, with a patch with largest values of slip and peak slip rate in a segment between 100 and 150 km from the hypocenter, and a second large patch of 100km

segment at the end of the fault. The no-ShakeOut asperity model has patches of large slip and peak slip rate uniformly distributed along the fault. These large patches seen in all the models are results from the high stress drop patches located at deep depth. This difference of patches distribution between the ShakeOut and no-ShakeOut scenarios has important implication on the ground motion, as will be seen in the next section.

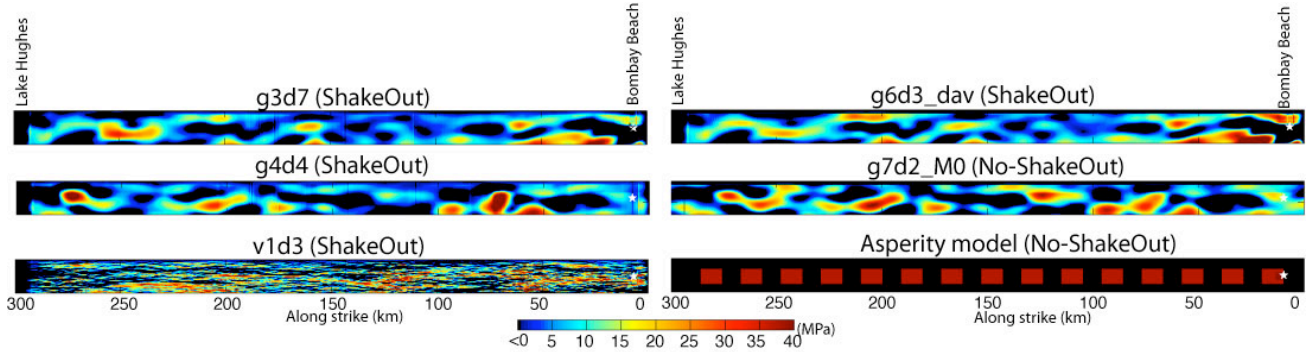


Figure 2. Dynamic stress drop distribution for the ShakeOut Scenario models with surface slip constraint (Gaussian models g3d7, g4d4, and Von Karman v1d3) and depth-averaged slip constraint (gaussian g6d3_dav), and No-ShakeOut scenario models (stochastic gaussian g7d2_M0 and asperity model). On the top figures, the Bombay Beach (rupture initiation) and Lake Hunghes (rupture termination) are placed.

Table 1 Average values of dynamic rupture scenarios

Model	ShakeOut	Average Stress drop (MPa)	Average peak slip rate (m/s)	Average slip (m)	Mw
g3d7	yes	4.8	4.0	3.4	7.76
g4d4	yes	4.7	4.0	3.4	7.75
v1d3	yes	5.4	4.8	3.5	7.79
g6d3_dav	yes	5.9	4.0	4.2	7.82
g7d2_M0	no	5.7	4.2	4.3	7.83
Asperity model	no	5.7	4.9	5.1	7.87

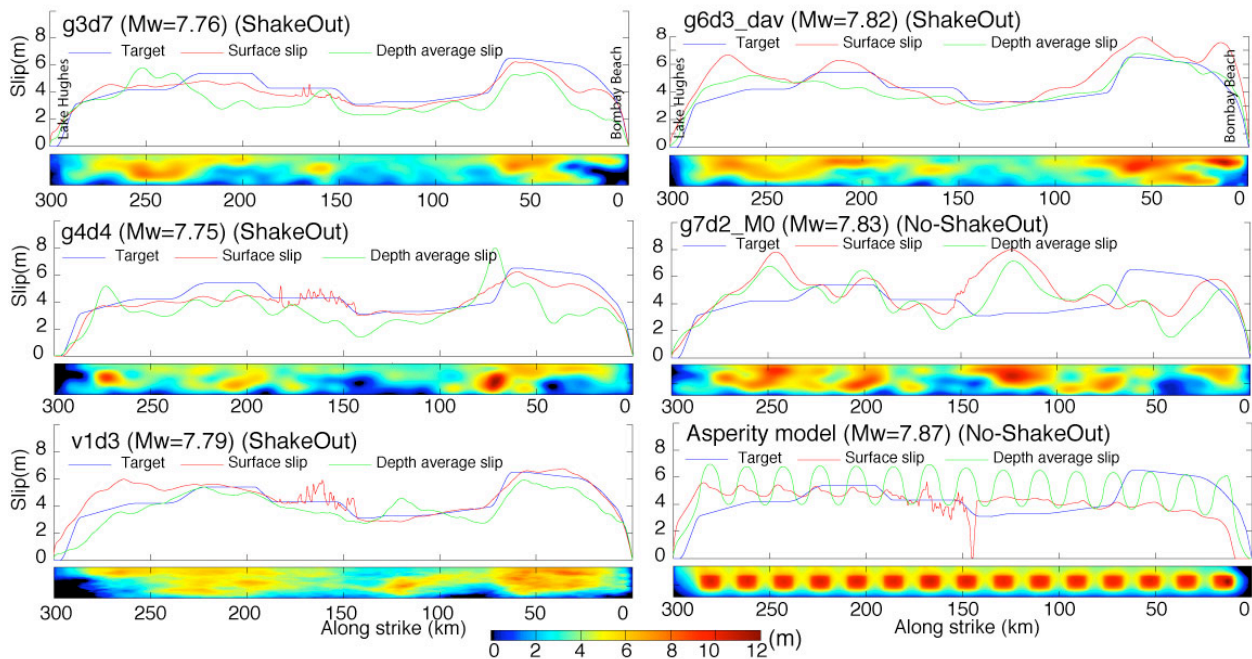


Figure 3. Surface slip (red line), depth-averaged slip (green line) compared with the target ShakeOut surface slip (blue line) and final slip distribution for the ShakeOut Scenario models with surface slip constraint (g3d7, g4d4, v1d3) and depth-averaged slip constraint (g6d3_dav), and No-ShakeOut scenario models (7d2_M0 and asperity model). On top figures, the Bombay Beach (rupture initiation) and Lake Hunghes (rupture termination) are placed.

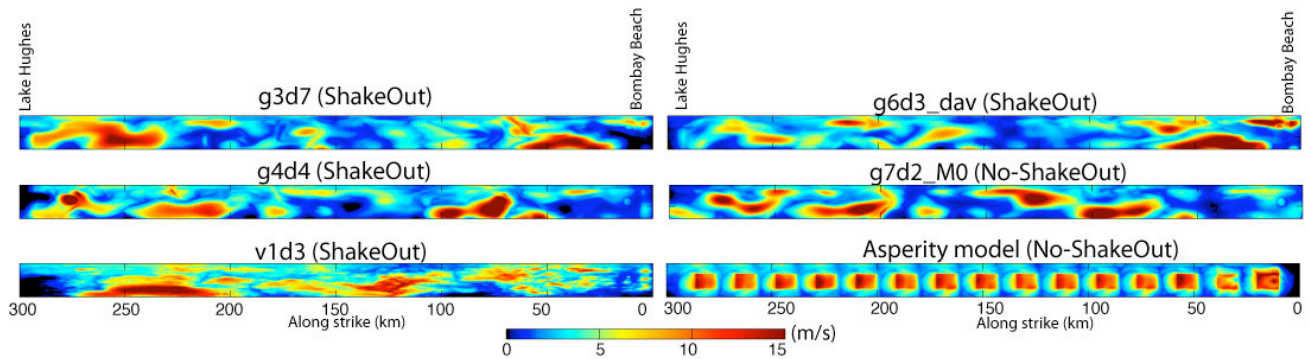


Figure 4. Peak slip rate distribution for the ShakeOut Scenario models with surface slip constraint (g3d7, g4d4, v1d3) and depth-averaged slip constraint (g6d3_dav), and No-ShakeOut scenario models (7d2_M0 and asperity model). On top figures, the Bombay Beach (rupture initiation) and Lake Hughes (rupture termination) are placed.

HORIZONTAL PGV OF DYNAMIC RUPTURE SCENARIOS

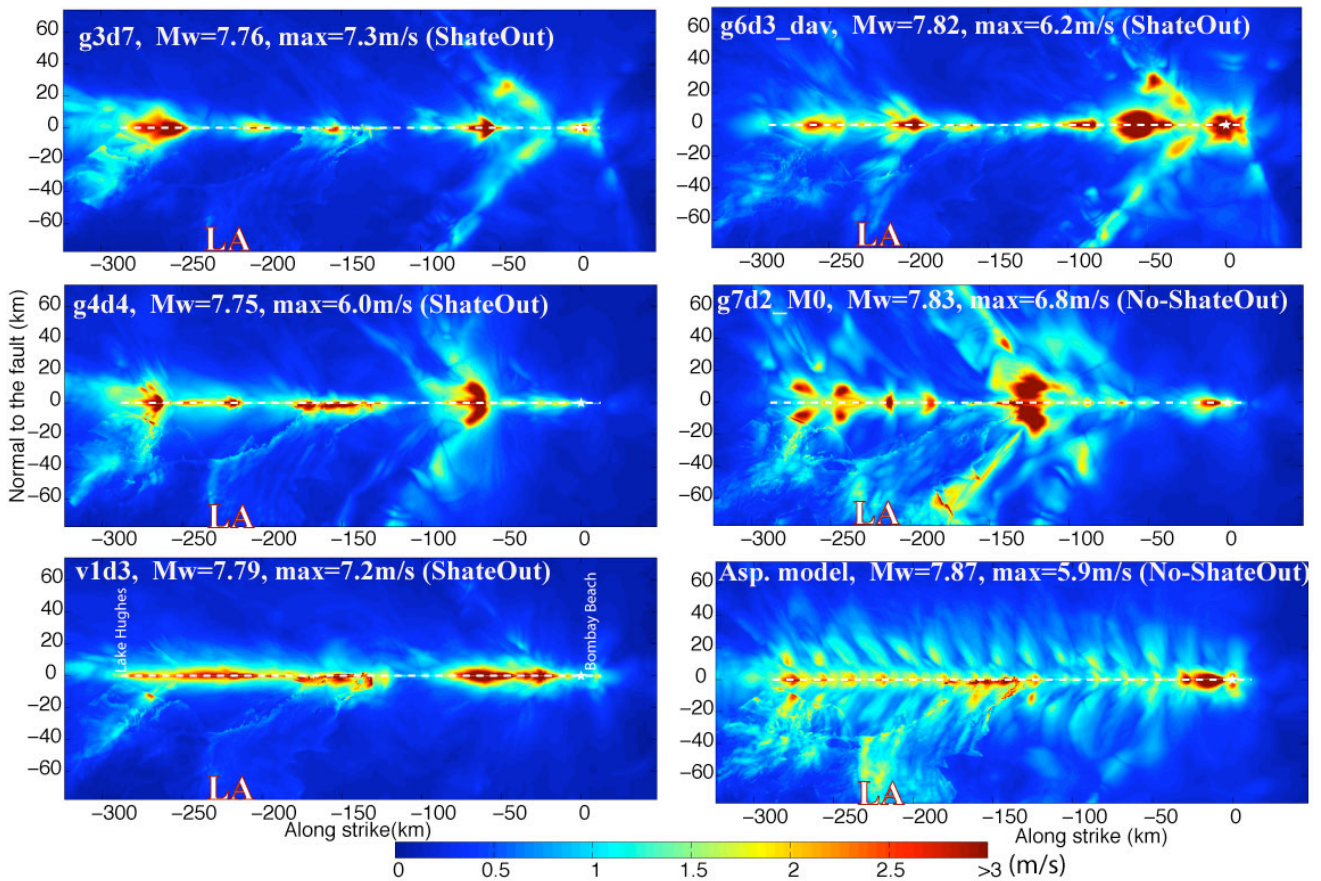


Figure 5. Horizontal peak ground velocity (PGV) ground motion for the ShakeOut Scenario models with surface slip constraint (g3d7, g4d4, v1d3) and depth-averaged slip constraint (g6d3_dav), and No-ShakeOut scenario models (7d2_M0 and asperity model). On the left bottom figure, the Bombay Beach (rupture initiation) and Lake Hughes (rupture termination) are specified. The LA placed on the bottom of all the figures, approximately corresponds to Los Angeles basin area.

4. NEAR SOURCE GROUND MOTION

The horizontal peak ground velocity (PGV) of the near source ground motion pattern generated by the ShakeOut and no-ShakeOut dynamic rupture models are qualitatively compared in Figure 5. The PGV is the direct result from the numerical simulation, corresponding to a maximum frequency of 0.5Hz run in the numerical simulation. The common feature between all the models is that the highest PGV values are just next

to the fault, above the largest patches of slip and peak slip rate described before. Even though the zero or negative stress drop at the first 2km depth, common in all the models, the deep high stress drop patches are driving the ground motion toward the free-surface. The LA placed on each image of Figure 5, approximately corresponds to Los Angeles basin. We focus our attention of the ground motion on this area. As seen in the figures, all the ShakeOut Scenarios produces lower ground motion than the no-ShakeOut scenarios. Notice that the energy channeling mechanism toward the LA basing is strongly excited in the no-ShakeOut scenarios. As early explained, this mechanism considerably magnifies the ground motion in Los Angeles area basin. The asperity model predicts the largest ground motion in LA. In spite that this asperity model also predict the largest moment magnitude, the uniform distribution of large patches of stress drop (asperities) along the strike of the fault seems to be the main responsible to excite the channeling mechanism. The no-ShakeOut g7d2_M0 model, that has patches of high stress drop randomly distributed along the fault, has closer features to the asperity model than the ShakeOut scenarios, the latter scenarios have larges patches of high stress drop located at the extremes of the fault, as result of constraint with the ShakeOut slip distribution profile. The large patches of high stress drop located between 100km and 150km from the hypocenter, in the no-ShakeOut g7d2_M0 model, seems to be the main responsible to generate higher ground motion in LA basin.

5. CONCLUSIONS

We have performed stochastic dynamic rupture models of moment magnitude around 7.8 with different source descriptions on the southern San Andreas fault. One group of models obeys the ShakeOut rupture scenario defined by the final slip profile estimated from geological observations. The other set of models are strictly no-ShakeOut scenarios. One of the no-ShakeOut scenario model results from the purely stochastic distribution input. The other no-ShakeOut dynamic model is an asperity model parameterized with the calibrated asperity model proposed by Dalguer et al., (2008). The rupture of all the models initiates near Bombay Beach and propagates unilaterally 300 km toward the northwest up to near Lake Hughes. The solution of these models shows a wide variety of complex rupture patterns, varying greatly in their fault-plane distributions of stress drop, peak slip velocity, final slip and rupture time. All the models generate the strongest ground motion next to the fault, driven mainly by the patched of high stress drop at deep depth. The characteristic of the ShakeOut scenarios, with final slip profiles defined either as surface slip or depth-averaged slip, produces similar pattern of ground motion at the Los Angeles basin. The no-ShakeOut scenarios generate the stronger ground motion at this place than the ShakeOut scenarios. This difference of ground motion in the LA basin between the type of models appears to be due to the distribution characteristic of large patches of stress drop along the fault. The ShakeOut scenarios have the large patches of high stress drop at the extremes of the fault, as result of the slip distribution profile used as constraint. However, the no-ShakeOut scenarios have the patched of high stress drop distributed along the fault. This feature of the no-ShakeOut scenarios is capable to excite the mechanism of energy channeling that considerably magnifies the ground motion in Los Angeles area basin. The asperity model predicts the strongest ground motion in LA because of the uniform distribution of large patches of stress drop (asperities) along the strike of the fault. These results suggest that the ShakeOut Scenario definition is in favor to generate lower ground motion in LA basin.

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