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Modelling earthquake ruptures with dynamic off-fault damage

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Earthquake rupture modelling has been developed for producing scenario earthquakes. This includes understanding the source mechanisms and estimating far-field ground motion with given a priori constraints like fault geometry, constitutive law of the medium and friction law operating on the fault. It is necessary to consider all of the above complexities of a fault systems to conduct realistic earthquake rupture modelling. In addition to the complexity of the fault geometry in nature, coseismic off-fault damage, which is observed by a variety of geological and seismological methods, plays a considerable role on the resultant ground motion and its spectrum compared to a model with simple planer fault surrounded by purely elastic media. Ideally all of these complexities should be considered in earthquake modelling. State of the art techniques developed so far, however, cannot treat all of them simultaneously due to a variety of computational restrictions. Therefore, we adopt the combined finite-discrete element method (FDEM), which can effectively deal with pre-existing complex fault geometry such as fault branches and kinks and can describe coseismic off-fault damage generated during the dynamic rupture. The advantage of FDEM is that it can handle a wide range of length scales, from metric to kilometric scale, corresponding to the off-fault damage and complex fault geometry respectively. We used the FDEM-based software tool called HOSSedu (Hybrid Optimization Software Suite - Educational Version) for the earthquake rupture modelling, which was developed by Los Alamos National Laboratory. We firstly conducted the cross-validation of this new methodology against other conventional numerical schemes such as the finite difference method (FDM), the spectral element method (SEM) and the boundary integral equation method (BIEM), to evaluate the accuracy with various element sizes and artificial viscous damping values. We demonstrate the capability of the FDEM tool for modelling earthquake ruptures. We then modelled earthquake ruptures allowing for coseismic off-fault damage with appropriate fracture nucleation and growth criteria. We studied the effect of different conditions such as rupture speed (sub-Rayleigh or supershear), the orientation of the initial maximum principal stress with respect to the fault and the magnitude of the initial stress (to mimic depth). The comparison between the sub-Rayleigh and supershear case shows that the coseismic off-fault damage is enhanced in the supershear case when compared with the sub-Rayleigh case. The orientation of the maximum principal stress also has significant difference such that the dynamic off-fault cracking is more likely to occur on the extensional side of the fault for high principal stress orientation. It is found that the coseismic off-fault damage reduces the rupture speed due to the dissipation of the energy by dynamic off-fault cracking generated in the vicinity of the rupture front. In terms of the ground motion amplitude spectra it is shown that the high-frequency radiation is enhanced by the coseismic off-fault damage though it is quickly attenuated. This is caused by the intricate superposition of the radiation generated by the off-fault damage and the perturbation of the rupture speed on the main fault.