

# Dynamics of shallow reverse faulting in 2D

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A number of authors have recently simulated shallow reverse and normal faulting. Oglesby et al (1997, 2000) have in particular noticed that the effects of the free surface on strong motion and rupture are much more important than previously thought. They attributed these effects to a “break in symmetry” due to the local stress field near the surface. Brune and colleagues (Brune and Anooshepor, 1998; Shi et al, 1998) have carried a set of experiments on a foam rubber model of a reverse fault and modelled it using a 2D lattice model. They found, among other things, that ruptures in the foam rubber model tended to produce an opening of the fault near the surface of the foam rubber specimen. This opening completely releases compressive strains reducing friction and producing non-linear deformation of the hanging wall. Brune (personal communication, 2000) has also found that the moment release measured directly from the foam rubber experiment does not match the moment computed by traditional seismological methods.

We have studied thrust faulting in a simple two dimensional in-plane fault model both in the static and kinematic approximations. For the static studies we used Okada’s results for a shear displacement discontinuity buried in a homogeneous half-space. We use this solutions in a Boundary Integral Equation Method (BIEM) similar to that developed by Fukuyama and Madariaga (1998) for elastodynamics in order to compute the static solution for faults loaded by different stress fields. The approach we use is inspired by a displacement discontinuity method proposed recently by Bonafede and Neri (2000). There is an older displacement discontinuity method in 2D proposed by Crouch (1977), but this author used the stress convention of rock mechanics so that some of the components of stress are reversed in sign.

We demonstrate that, near the free surface, the plane stress field around the fault becomes one of plane stress. In plane stress the vertical and horizontal strains along the surface are related by

$$\epsilon_{xx} = -\frac{\lambda + 2\mu}{\lambda}\epsilon_{yy} \quad (1)$$

This relation insures that the vertical stress  $\sigma_{zz} = 0$  at  $z = 0$ . During reverse faulting stresses relax so that  $\sigma_{xx}$  and  $\epsilon_{xx}$  are positive (horizontal stretching); and  $\epsilon_{yy}$  is negative (vertical compression). This free-surface effect is responsible for some additional terms in the dislocation field that are not present in the classical dislocation models used in seismology.

The stress field of a dislocation near a free surface contains three terms: (1) that due to the fault as if were buried in an infinite space, (2) its image by the free surface and (3) the effect of plane stress conditions explained above. The latter term provides the necessary horizontal force to equilibrate the fault when it breaks the free surface, so that the double couple representation is correct at low frequencies. Our results show that the free surface effects considered by Nielsen (1998) and Oglesby et al (1998, 2000) are a particular case for the static fault.

As shown by Bonafede and Neri (2000), the free surface effects are only a fraction of the effect of stress drop for shear faulting when the friction coefficient is less than 1. The effect of the free surface depends mainly on the angle of the preexisting fault with respect to the free

surface. For foam rubber, whose friction coefficient is much larger than 1, fault “dcollement” is predicted for all faults that intersect the surface at shallow angles.

We also study the field of a thrust dislocation propagating along a shallow fault. The solution for displacements near the free surface and the interior of the earth were computed by Madariaga (1979), but he computed only a very particular example inspired by the San Fernando earthquake. Here we extend the theory to compute the complete strain and stress field in a half space near the free surface. We demonstrate that this problem is surprisingly simple: a fault can be represented as a fixed dislocation at the hypocenter plus a moving one that climbs along the fault plane. Free surface effects are much more complex than those of the static fault. They include the four types of reflections from the free surface. These waves interfere to generate Rayleigh waves. The plane stress condition defined above appears in the wake of the Rayleigh wave, so that it is not clear whether static effects can be used to understand the dynamics. The complete field produced by a moving dislocation near a free surface can be computed exactly using the Cagniard-de Hoop method as in Madariaga (1979). But its practical use is difficult. Nowadays, it is much more efficient for practical applications to compute the field of the dislocation using a spectral method like Bouchon’s frequency-wave number integration. Using our elementary fault solution we can set up a displacement discontinuity method just like Fukuyama and Madariaga (1978) did for 3D dynamic faulting. Unfortunately the programming of the BIEM method is difficult and I have not been able to get results yet.

From our analysis of the kinematic model it appears that a moving dislocation approximation near the rupture front is just as valid as in the case of the fault embedded in a full space. To the highest order the formulas developed by Ida (1972) for in-plane loading remain valid with some changes in the influence coefficients. Once again the effect of the free surface depends on the dip angle of the fault. Most of the results from modeling can be explained by the interaction of reflected phases with the rupture process on the fault and the directivity of S-waves. Dislocation models take into account the latter effect but can not properly handle diffraction of reflected waves by the fault. A complete understanding of Shi and Oglesby’s numerical results will have to wait until we have a working implementation of the half-space BIEM.

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