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Three-dimensional finite-element modelling of coseismic Coulomb stress changes on intra-continental dip-slip faults

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ABSTRACT

Investigating fault interaction plays a crucial role in seismic hazard assessment. The calculation of Coulomb stress changes allows quantifying the stress changes on so-called receiver faults in the surrounding of the fault that experienced the earthquake. A positive stress change implies that the earthquake brought the receiver fault closer to failure while a negative value indicates a delay of the next earthquake. So far, most studies focussed on stress changes for particular faults and earthquakes. Here we present a general analysis of the Coulomb stress changes on intra-continental dip-slip faults using finite-element models with normal and thrust faults arrays, respectively. Our models allow calculating coseismic ("static") stress changes on pre-defined fault planes, whose dip and position can be varied. Gravity and ongoing regional deformation (i.e. shortening or extension) are included. The results for thrust and normal faults show that synthetic receiver faults located in the hanging wall and footwall of the source fault exhibit a symmetric stress distribution, with large areas of negative and small areas of positive Coulomb stress changes. In contrast, faults positioned in along-strike prolongation of the source fault and outside of its immediate hanging wall and footwall undergo mostly positive stress changes. The stress changes are largest at the fault tip that is closer to the source fault. Our results show that the stress change distribution depends on the fault dip while the magnitude depends on the friction coefficient and the amount of coseismic slip. The Coulomb stress changes can be explained by the spatial distribution of the coseismic strain, which shows domains of horizontal extension and shortening that alternate both at the surface and with depth. Our models allow identifying the general patterns of Coulomb stress changes on dip-slip faults, which are often concealed by the peculiarity of the specific fault or earthquake in nature.

1. Introduction

Earthquakes on intra-continental faults pose a substantial seismic hazard to populated areas, however, their potential to cause moderate to large earthquakes has received less attention than the earthquake hazard at plate boundaries (England and Jackson, 2011). This is at least partly due to the fact that faults in continental interiors have usually much lower slip rates (typically ≤1–2 mm/a) and hence longer earthquake recurrence intervals than plate boundary faults. As a consequence, no historic records may be available to document their capability to produce earthquakes. Recent examples of devastating intracontinental earthquakes include the 2003 Bam (Iran) (Fu et al., 2004), 2009 L'Aquila (Italy) (Serpelloni et al., 2012) and the 2008 Wenchuan (China) (Shan et al., 2013; Wang et al., 2014a) earthquakes. In addition to the immediate damage, a large earthquake on a source fault can also cause stress changes on adjacent faults (= receiver faults), which may ultimately trigger or delay other earthquakes. Hence, investigating the interaction of faults plays a crucial role in the assessment of future seismic risks. The stress change due to an earthquake is commonly calculated as the change in the Coulomb failure stress ΔCFS (e.g., Freed, 2005; Stein, 1999, 2003; Stein et al., 1992):

$$\Delta CFS = \Delta\tau - \mu' \Delta\sigma_n$$

where $\Delta\tau$ is the change in shear stress (positive in direction of slip of the source fault), μ' is the effective coefficient of friction and $\Delta\sigma_n$ is the change in normal stress (positive if fault is clamped). If ΔCFS is positive, the receiver fault has been brought closer to failure; a negative value of ΔCFS implies that the next earthquake is delayed. Note that already a Coulomb stress change of 1 bar (0.1 MPa) on the receiver faults may trigger an earthquake on the receiver faults (King et al., 1994).

Analysis of Coulomb stress changes was first widely applied to strike-slip faults, at least partly because the vertical orientation of the fault planes facilitated the calculation of the stress changes. For example, King et al. (1994) showed that the 1992 M = 7.4 strike-slip Landers earthquake triggered the M = 6.5 strike-slip Big Bear aftershock by a static Coulomb stress increase of 0.3 MPa. An interaction between the 1999 strike-slip Hector Mine earthquake and the Landers earthquake was controversially discussed, because the Hector Mine earthquake

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was located in the transition zone between stress-triggering and stress-shadow zones of the Landers earthquake. In this discussion, other mechanisms invoked for the link between the Landers and Hector-Mine earthquakes were dynamic stress changes (caused by seismic waves) and postseismic relaxation, which may cause transient Coulomb stress changes (e.g. Cianetti et al., 2005; Freed, 2005; Freed and Lin, 2001; Masterlark and Wang, 2002). Many other calculations of coseismic Coulomb stress changes on strike-slip faults exist; for example, the 1999 $M_w = 7.4$ Izmit earthquake at the dextral strike-slip North Anatolian fault was successfully predicted by Stein et al. (1997) using the calculation of the coseismic Coulomb stress changes.

First studies on Coulomb stress changes on dip-slip faults were carried out in Italy after the 1980 Irpinia normal fault earthquake and revealed similar triggering effects as for strike-slip faults. Due to the 1980 Irpinia (Italy, southern Apennines) normal fault earthquake, the coseismic Coulomb stress increased on the nearby dextral Potenza fault, which was ruptured by earthquakes in 1990 and 1991 (Nostro et al., 1997). Similarly, the 2004–2008 normal fault earthquake sequence at the South Lunggar Rift (Tibet) was explained by the Coulomb stress changes (Ryder et al., 2012). The 2004 earthquake increased the Coulomb stress at the synthetic receiver fault on the same side of the graben, which experienced an earthquake in 2005. As a consequence of the 2005 earthquake, the Coulomb stress increased both antithetic receiver faults on the other side of the graben, which were ruptured in 2008 (Ryder et al., 2012). Similar fault interactions after major earthquakes were inferred for contractional tectonic settings. For example, Lin et al. (2011) linked the majority of the aftershocks of the 2003 $M_w = 6.9$ thrust fault Zemmouri (Algeria) earthquake to an increase in coseismic Coulomb stress change. The analysis of static Coulomb stress changes after the 2008 $M_w = 7.9$ Wenchuan earthquake, which ruptured the Beichuan and Pengguan reverse faults (Jia et al., 2010), showed that this oblique thrust event caused considerable positive and negative static Coulomb stress changes on faults in the region (Luo and Liu, 2010; Parsons et al., 2008; Toda et al., 2008; Wang et al., 2014a).

In contrast to the number of studies that calculated Coulomb stress changes for particular faults and earthquakes, studies analysing general Coulomb stress patterns on dip-slip source and receiver faults are sparse. Maps of Coulomb stress changes for strike-slip faults parallel to the source fault were presented by King et al. (1994). Based on the thrust and strike-slip fault array that included the source fault of the 2003 Zemmouri earthquake, Lin et al. (2011) calculated the Coulomb stress changes for different positions of the receiver faults relative to the source fault. Recently, Wang et al. (2014a) showed in a systematic investigation using the setting of the 2008 Wenchuan earthquake that Coulomb stress changes are sensitive to the coseismic slip of the source fault, the friction coefficient as well as the orientation of the receiver fault. The correct slip distribution is particularly important, because the stress change highly depends on the slip distribution on the source fault (Wang et al., 2014a). With respect to the slip distribution, it should be noted that many models directly prescribe the coseismic slip in a simplified way, for example, by defining the way in which the coseismic slip decreases from a maximum value in the fault centre to zero at the fault edges. Other models use the slip distributions derived from inverse modelling of geodetic data, which implies that the slip distribution highly depends on the local geological conditions and on the data coverage.

Here we present three-dimensional finite-element models to investigate – independent of a specific fault or earthquake – the general patterns of coseismic Coulomb stress changes for arrays of normal and thrust faults, respectively. Each fault array consists of a source fault in the centre and ten receiver faults located along-strike of the source fault as well as in its hanging wall and footwall. Slip on the source fault is not prescribed but evolves freely as a function of the length of the preseismic phase and the rate of regional extension or shortening. In other words, the coseismic slip on our model source fault evolves self-consistently throughout the entire model run. We use our models to perform a systematic study about the spatial distribution of the coseismic Coulomb stress change and to link these stress changes to the distribution of the coseismic strain at the model surface and at depth. Based on a series of experiments, we evaluate the effects of fault dip and dip direction (synthetic, antithetic), friction coefficient and coseismic slip on the coseismic Coulomb stress changes.

2. Model setup

We use three-dimensional finite-element models generated by the commercial software Abaqus (version 6.13). All models are 200×200 km wide and represent a 100-km-thick continental lithosphere (Fig. 1), which is subdivided in a 15-km-thick elastic upper crust, a 15-km-thick viscoelastic lower crust and a 70-km-thick viscoelastic lithospheric mantle. The elastic parameters (Young's modulus E, Poisson's ratio ν), the density ρ and the viscosity η of the layers are shown in Fig. 1. Viscoelastic behaviour is implemented as linear, temperature-independent Maxwell viscoelasticity. Although this rheology represents a simplification of the actually depth-dependent and possibly non-linear viscoelastic behaviour of the lower crust and lithospheric mantle (e.g., Ellis et al., 2006; Freed and Bürgmann, 2004), the implementation of viscoelastic layers itself is an advantage compared to the commonly used homogeneous elastic halfspace models based on Okada (1992) because our models can be used to analyse transient Coulomb stresses caused by postseismic viscoelastic relaxation in future studies. Our models also include isostatic effects, which we simulate by applying a lithostatic pressure of 3×10^9 Pa and an elastic foundation to the model bottom. The property of the elastic foundation represents an asthenosphere with a density of 3200 kg/m^3. Gravity is included as a body force (acceleration due to gravity: $g = 9.81$ m/s^2). The model sides in the xz-plane are fixed in the y-direction, while the bottom is free to move in the vertical and horizontal directions.

We created two reference models with arrays of normal faults (dip: 60°; Fig. 1a) and thrust faults (dip: 30°; Fig. 1b), respectively. All faults are 40 km long and extend from the model surface to the bottom of the upper crust. The faults are modelled as frictional contact interfaces between the footwall and hanging wall of each fault. The minimum distance between the faults is 15 km in the x-direction (e.g. between faults 4 and 5) and 5 km in the y-direction (e.g. between tips of faults 1 and 4). The fault in the centre (fault 6; see Fig. 1) represents the source fault, which will experience the coseismic slip during the modelled earthquake cycle. The other faults in its surrounding represent the receiver faults, for which the Coulomb stress changes induced by the earthquake will be analysed (see Fig. 1 for the spatial configuration of the receiver faults). The general distance between the faults in the x-direction is 30 km, which is a typical spacing between faults, for example, in the Basin and Range Province (Wernicke et al., 2000). To capture the Coulomb stress changes near the source fault, we placed two additional model faults (5, 7) in the hanging wall and footwall of the source fault at a distance of 15 km. By applying a velocity boundary condition at the model sides in the yz-plane, the model either is extended or shortened at a total rate of 6 mm/a, which initiates slip on the faults. Slip initiation is controlled by the Mohr–Coulomb criterion $|\tau_{max}| = C + \mu\sigma_n$, where τ_{max} is the critical shear stress, C is the cohesion (zero in our model), σ_n is the normal stress and μ the friction coefficient, which has value of 0.6 in the reference model. Additional experiments were run with a value of 0.4. These values represent intermediate coefficients of friction for intra-continental faults, which range from about 0.3 to 0.8 (Collettini et al., 2009; Hurd and Zoback, 2012; Niemeijer and Collettini, 2014; Townend and Zoback, 2000). Apart from that, friction coefficients of 0.4 and 0.6 are commonly used in Coulomb stress calculations (e.g. Lin et al., 2011; Nostro et al., 1997; Ryder et al., 2012), which facilitates the comparison with these previous studies. In contrast, the friction coefficient may approach zero on mature plate boundary faults with large displacements, such as the San