Stress redistribution following unwelding of near-surface layers in strike-slip fault zones

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SUMMARY

Major strike-slip earthquakes are often associated with a complex pattern of surface fractures, organized in hierarchical order (en-echelon shear fracture arrays, open tensile fractures and hillocks), which are oriented differently from the strike of the main fault and often extend laterally 1 or 2 km. In the attempt to understand why the main fault remains confined at depth, we have considered the possibility that, during the earthquake, a soft shallow sedimentary layer unwelds from the lower basement rock along a horizontal interface. The stress redistribution provided by the unwelding process in the shallow layer is studied in terms of a dislocation model employing the boundary-element method. We show that a nearly uniform Coulomb failure function develops above the main fault, over a km-wide strip along the fault strike (explaining shear fracture arrays) and positive tensile stresses appear near the surface over a similarly wide strip (explaining open fractures). A parametric study is performed to show when the unwelding process can take place and how the resulting stress redistribution in the shallow layer depends on the depth of the unwelded layer and on the coefficient of friction.

Key words: Numerical solutions; Rheology and friction of fault zones; Continental tectonics: strike-slip and transform; Dynamics and mechanics of faulting; Fractures and faults.

1 INTRODUCTION

Transcurrent tectonics plays an important role in many seismic areas of the Earth. Major transcurrent earthquakes generally determine complex rupture zones at the Earth’s surface and many authors have studied and classified the observed structures to investigate their generation processes. Often, the main fault remains buried at depth and en-echelon arrays of secondary shear fractures are observed at the surface, which are generated in close connection with the main slip event but possess different strike direction and extend laterally 1 or 2 km from the main fault strike; sometimes, open fractures and hillocks are present along secondary fractures, which can be considered third-order structures and possess still different strike direction. Deng et al. (1986) gave an overview of the structure and the deformational character of strike-slip fault zones studying four different strike-slip rupture zones in China. They found that the geometry of rupture zones can be described essentially in terms of the arrangement (pinnate or en-echelon), the type of step (left step or right step) and the hierarchic rank of the subparallel faults observed at the surface. A schematic diagram of fault zone complexities is shown in Fig. 1.

The complexity of the surface structures is generally interpreted in terms of a redistribution of the stress release in the shallower crustal layers. If the medium is assumed to be a homogeneous half-space, a complex pattern of surface fractures may be explained in terms of the interaction among differently oriented sections of the main fault. However, the main fault at depth has often much simpler geometry than its surface expression, as shown by relocated aftershocks and by geodetic inversions of fault slip (see, e.g. the earthquakes of 2000 June in the South Iceland Seismic Zone, SISZ, Stefansson et al. 2011); in such cases, the fault zone complexity may be explained by the heterogeneities of the medium.

One of the main unanswered questions regarding the surface fracture pattern is: why the main fault does not propagate directly up to the surface? Many authors have studied fracture propagation in inhomogeneous media and Rybicki & Yamashita (1998) have shown that low rigidity media may represent a barrier for fracture propagation. Furthermore, Bonafede et al. (2002) found that a planar vertical crack cutting across a welded interface must satisfy a stress drop discontinuity condition. If this condition cannot be satisfied, as typically happens in presence of friction, the main fault cannot continue across the interface and fault bending and branching may take place. If we consider a transform boundary in a horizontally layered medium, with vertical coordinate $z$, the incremental stress produced by tectonic shear over a vertical plane is proportional to the local rigidity value. Therefore, the traction over a vertical fault plane drops abruptly while passing from the rigid half-space to the soft shallow layer. The same does not apply to the stress components acting on the horizontal interface $z = H$, since tractions must be continuous across a plane. This entails that the fracture condition may be preferably met on a horizontal plane rather than on the vertical prolongation of the main fault, up into a soft shallow layer.

The stress release perturbation in the shallow layers may justify the development of different fracture processes for the individual
The aim of this paper is to model a self-consistent generation mechanism of secondary fault structures induced by the interaction of the main fault with structural heterogeneities at shallow depth. We consider a horizontally layered medium, with the upper layer weakly welded to the bedrock, due to the presence of low-strength material along the interface (e.g. pyroclastic debris between lava layers). We study if and how the presence of this weak interface may produce the decoupling between the elastic layers and determine a redistribution near the free surface of the stress released by the main fault. This process is analysed in the framework of 2-D dislocation models, developing a numerical procedure based on the displacement discontinuity method (Crouch & Starfield 1983). We model the interface unwelding in terms of two secondary shear fractures that develop in opposite directions along the interface. The mechanism proposed in this paper represents a special case of fault branching, in which the two secondary induced fractures do not penetrate into the surface layer but instead develop along the interface. The unwelding of the interface and the stress release in the shallow layer are studied in terms of model parameters to evaluate in which cases the model can be useful to describe surface structures which are typical of strike-slip rupture zones.

### 2 Model Description

The total stress after an earthquake is given by the sum of three contributions: the lithostatic stress, the deviatoric stress (regional stress) present before the earthquake and the seismic stress change produced by the rupture at depth. In this paper, we do not refer to a specific geodynamic context, thus we ignore the regional stress and only the other two terms shall be taken into account. This approximation seems reasonable, because we shall study in particular the regions where the seismic stress change is high.

According to the Coulomb failure criterion, the opening of shear fractures takes place on the plane where the traction overcomes the frictional threshold. In presence of friction, the orientation of the optimal plane is dependent on the normal stress. Considering a bidimensional state of stress, the orientation of the vertical plane is given by \( \theta \) (Fig. 2), the angle formed by the plane with the compressive axis (correspondent to the negative principal stress)

\[
\theta = \pm \frac{1}{2} \arctan(1/f) \quad \text{(Turcotte & Schubert 1982)}
\]

If \( f = 0 \) we have \( \theta = \pm \frac{\pi}{4} \) and the optimal planes are the planes of maximum shear traction; if \( f \) increases \( \theta \) decreases and the opening of secondary shear fractures shall take place closer to the principal tensional plane. The optimal planes represent the planes where the Coulomb failure function (CFF)

\[
CFF = |\tau| + f (\sigma_n + p)
\]

assumes its maximum value (\( \tau \) is the shear stress, \( f \) the friction coefficient, \( \sigma_n \) the normal stress and \( p \) is the pore pressure). Considering different sets of values of the model parameters, we shall study how the process of unwelding affects the stress field in a soft...
density \( \rho \) and density \( \rho \). Sketch of the model: a soft layer (0 ≤ \( z \) ≤ \( H \)) lies above a hard half-space (\( z > H \)) with rigidity \( \mu_1 \) and density \( \rho_1 \). The slip \( \Delta u \) of a vertical main fault MF embedded within the half-space is accompanied by unwelding of the layer along the horizontal sections \( HD^+ \) of the interface \( z = H \).

Shallow layer. The opening of tensile fractures shall be studied in a similar way, evaluating the maximum opening stress (MOS), which is defined as the principal tensile stress of the stress tensor given by the sum of the lithostatic stress and the stress change induced by faulting.

We consider a system in which a shallow elastic layer is separated along a weakly welded interface from the deeper brittle crust (Fig. 3). The low-rigidity upper layer can represent a sedimentary deposit which decouples from the deeper crust when a suitable stress threshold is overcome. The origin of the reference system is at the free surface and the interface between the shallow layer and the half-space is at the depth \( z = H \). A rigidity contrast is present at the interface since the layer has rigidity \( \mu_1 \), whereas the half-space has higher rigidity \( \mu_2 \) (\( m = \mu_2/\mu_1 > 1 \)). An antiplane strain configuration is considered, in which the only non-vanishing component of the displacement field is \( u_y(x, z) \), which is independent of the \( y \)-coordinate, so the only non-vanishing components induced by crack slip are \( \sigma_{0y}, \sigma_{0z} \). At the free surface, where \( \sigma_{0y} = 0 \), the principal stress axes are the bisectors of the quadrants in the \( xy \)-plane (Fig. 2).

The main fault \( \text{MF} \) considered is a transcurrent dextral fault, buried in the half-space, and the unwelding process is described in terms of two horizontal dislocations \( \text{HD}^+, \text{HD}^- \), slipping in opposite directions, at the interface from \( x = l_1 \) to \( x = l_2 \) and from \( x = -l_1 \) to \( x = -l_2 \) (Fig. 3). We consider a 2-D model and the dislocations are infinite along the strike direction \( y \). To define the unwelded region, the stress component \( \sigma_{0z} \) induced over the interface \( z = H \) is compared with the frictional threshold \( f(\rho_1 - \rho_2)gH \), where \( f \) is the coefficient of friction, \( \rho_1 \) is the rock density of the shallow layer, \( \rho_2 \) water density, \( g \) is gravity. In the following sections, a numerical model is deployed describing the unwelding process according to dislocation theory. Finally, the position and the extent of the unwelded region will be studied in terms of model parameters.

3 NUMERICAL APPROACH

The main fault \( \text{MF} \) and the horizontal dislocations \( \text{HD}^+, \text{HD}^- \) are characterized by a non-uniform displacement discontinuity over the dislocation surface (Somigliana dislocations). We assume that the \( \text{MF} \) is characterized by a uniform stress drop and that unwelding takes place with variable slip to release stress in excess of the frictional threshold. To solve the inverse dislocation problem, we use the displacement discontinuity method (Crouch & Starfied 1983) employing the elementary dislocation solutions in a layered medium provided by (Rybicki 1971, vertical strike-slip dislocation) and by (Singh & Rani 1994, horizontal strike-slip dislocation) (see Appendix).

3.1 Boundary element decomposition

The implementation of this numerical technique involves the decomposition of \( \text{MF} \), \( \text{HD}^+ \) and \( \text{HD}^- \) in boundary elements. The convenient way to effect this decomposition must be selected according to the geometrical properties of the model and to the features of the numerical method. Our target is to evaluate the stress release in the shallow layer (thickness \( \sim 10^2 \)–\( 10^3 \) m) and therefore we must assure that numerical solutions provide optimal resolution in this region. The displacement discontinuity method has a non-uniform accuracy which is optimal in the regions far from the boundary element (far field) and gets worse approaching it (near field). Since the investigated domain is close to the interface, we must guarantee that the boundary element widths be sufficiently small compared with their distances from the interface. The large extent of the \( \text{MF} \) (\( \sim 10^2 \) m) and its orientation (vertical with respect to the interface) suggest adopting a non-uniform decomposition for this boundary to reduce computational time without loss of accuracy (in Fig. 4, slip profiles are shown for increasing number \( N \) of \( \text{MF} \) elements). \( \text{HD}^+, \text{HD}^- \) are at the interface and therefore on this boundary it is quite natural to adopt an uniform decomposition. The number \( M \)
of the boundary elements covering \( HD^+\), \( HD^-\) is not fixed \textit{a priori} since the extent of the unwelded region is dependent from model parameters. This number is retrieved from the numerical procedure imposing the condition \( w_{iHD} < w_0\), where \( w_{iHD}\) is the width of the elements on the horizontal boundary and \( w_0\) is the width of the MF boundary elements close to the upper tip.

3.2 Crack interaction and identification of the unwelded region

The way the cracks interact and the identification of the unwelded region are strictly related problems. In the following, we describe two different approaches to study the interaction between the cracks and later we shall show how the different assumptions affect the main features of the unwelded region.

3.3 Method I: no back-interaction from \( HD^+\), \( HD^-\) onto MF

We assume that the back-interaction exerted by \( HD^+\), \( HD^-\) on the MF is not significant and therefore the width of the unwelded region is controlled only by the stress released by the MF. To identify the tips of the unwelded region, the stress component \( \sigma_{zy}\) induced on the interface by the slip of MF is compared with the frictional threshold. The first step is to assign the MF domain, from \( z = z_{01} \geq H\) (the upper tip) to \( z = z_{02}\) (the bottom tip), discretize this domain in \( N\) subintervals with midpoints in \( z = z_i\) (\( i = 1, \ldots, N\)) and then determine the crack slip \( \Delta u_i \) for the \( i\)th element of the MF in order that the stress drops by \( \Delta \sigma\) in \( z = z_i\). Accordingly, the following linear system is obtained:

\[
 t^i_k = -\Delta t^i_k = \sum_{j=1}^{N} A_{ij}^k \delta_{ij},
\]

where

\[
 \Delta t^i_k = \Delta \sigma, \quad 1 \leq k \leq N
\]

is the stress \( \sigma_{zy}\) in \( z = z_i\) due do the slips \( \delta_{ij}\) of the \( N\) elements of the MF and \( A_{ij}^k\) is an \((N \times N)\) matrix containing the influence coefficients of the traction that are computed according to eq. (A3).

The stress drop \( \Delta \sigma\) is assumed to be uniform and the system (3) is solved for the unknown slips \( \delta_{ij}\).

Once the previous system is solved, it is possible to determine the stress \( \sigma_{zy}\) induced by the MF over the interface \( z = H\) and the unwelded intervals \([-l_2, -l_1]\) and \([l_1, l_2]\) are obtained from the condition \( |\sigma_{zy}| > f(\sigma_{zy} - \rho)\). We assume that \( \sigma_{zy} = \rho g H\) is the lithostatic pressure and \( \rho = \rho g H\) is the hydrostatic pressure. Then, the crack slip on the dislocations \( HD^+, HD^-\) at the interface is obtained solving the following linear system:

\[
 t^i_+ = -\Delta t^i_+ = \sum_{j=1}^{M} A_{i,j}^+ \delta_{ij} + \sum_{j=N+1}^{N} A_{i,j}^- \delta_{ij},
\]

\[
 t^i_- = -\Delta t^i_- = \sum_{j=1}^{M} A_{i,j}^- \delta_{ij} + \sum_{j=N+1}^{N} A_{i,j}^+ \delta_{ij},
\]

where

\[
 H \left\{ \begin{array}{l}
 \Delta t^i_+ = t^i_+ - f(\rho_1 - \rho_0)gH, \\
 \Delta t^i_- = t^i_- + f(\rho_1 - \rho_0)gH, \\
 \end{array}\right. 1 \leq i \leq M.
\]

\( \Delta t^i_+, \Delta t^i_-\) are the stress components \( \sigma_{zy}\) in excess of the frictional threshold induced by the MF on the \( i\)th boundary element of \( HD^+\) and \( HD^-\), respectively. \( A_{i,j}^+, A_{i,j}^-\) are \((M \times M)\) matrices containing the influence coefficients of the traction that are computed according to eq. (A6).

3.4 Method II: complete interaction between the MF and the horizontal dislocations

In this approach, we assume that the back-interaction exerted by \( HD^+\), \( HD^-\) on the MF cannot be neglected. The opening of the horizontal dislocations \( HD^+\) produces a redistribution of crack slip on the MF. Therefore, even the \( \sigma_{zy}\) stress release at the interface may be significantly affected and may determine the narrowing or the widening of the unwelded region. To account for this, it is necessary to implement an iterative procedure which must be repeated until a stable solution is obtained.

Schematically, the following procedure will be performed:

1. Evaluate the MF slip due to stress drop \( \Delta \sigma\);
2. Evaluate \( \sigma_{zy}\) in \( z = H\) and obtain preliminary ends of \( HD^+\);
3. Evaluate slip functions on \( MF, HD^+\) and \( HD^-\) to release \( \Delta \sigma\) on MF and tractions in excess of the frictional threshold on \( HD^+\);
4. Re-evaluate \( \sigma_{zy}\) in \( z = H\) and obtain new estimates of \( HD^+\) ends;
5. Iterate steps 3 and 4 until a stable estimate is obtained.

More specifically, steps 1 and 2 involve the use of Method I to obtain preliminary estimates of \( HD^+\) tips whereas, in step 3, the distribution of slip on each crack section is determined solving the following linear system:

\[
 t^i_+ = -\Delta t^i_+ = \sum_{j=1}^{M} A_{i,j}^+ \delta_{ij} + \sum_{j=N+1}^{N} A_{i,j}^- \delta_{ij} + \sum_{j=1}^{N} A_{i,j}^k \delta_{ij},
\]

\[
 t^i_- = -\Delta t^i_- = \sum_{j=1}^{M} A_{i,j}^- \delta_{ij} + \sum_{j=N+1}^{N} A_{i,j}^+ \delta_{ij} + \sum_{j=1}^{N} A_{i,j}^m \delta_{ij},
\]

\[
 t^i_k = -\Delta t^i_k = \sum_{j=1}^{N} A_{i,j}^k \delta_{ij},
\]

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where

\[
\begin{align*}
\Delta t_{i+}' &= -f(\rho_1 - \rho_w) g H, \quad 1 \leq i \leq M, \\
\Delta t_{i-}' &= f(\rho_1 - \rho_w) g H, \quad 1 \leq i \leq M, \\
\Delta t_i' &= \Delta \sigma_i, \quad 1 \leq k \leq N,
\end{align*}
\]

where \(\Delta t_{i+}'\), \(\Delta t_{i-}'\) are the frictional threshold on the \(i\)th boundary element of \(HD^+\) and \(HD^-\), respectively, and \(\Delta t_i'\) is the uniform stress drop imposed on each boundary element of the MF. \(A_{i,i+1}', A_{i+1,i}', A_{i,i-1}', A_{i-1,i}'\) are \((M \times M)\) matrices containing the influence coefficients of the traction that are computed according to eq. (A6), while \(A_{i,i}', A_{i,i}'\) are \((N \times M)\) matrices containing the influence coefficients computed according to eq. (A7). \(A_{i+k,i}', A_{i+k,i}'\) are \((M \times N)\) matrices and \(A_{i+k,i}'\) is an \((N \times N)\) matrix containing the influence coefficients of the traction that are computed according to eqs (A2) and (A3), respectively.

The following criterion is employed to end the iterative procedure: at step 2, the values \(l_{1}^k, l_{2}^k\) (which represent a preliminary estimate for the positions of crack tips) are determined considering only the stress released by the main fault (as done in Method I): \(HD^+\) - slip over the plane \(z = H\) if and where \(|\sigma_2(MF)| \geq f(\rho_1 - \rho_w) g H\).

At step 3, since the positions of the unwelded regions have been estimated, \(\sigma_2\) is recalculated considering the contributions of all the interacting cracks \((MF, HD^+\) and \(HD^-\)) and the values \(l_{1}^{(2)}, l_{2}^{(2)}\) are found by comparison with the frictional threshold (step 4). The values \(l_{1}^{(2)}, l_{2}^{(2)}\) are assumed as acceptable estimates for the position of crack tips if the following condition is met:

\[
|l_{1}^{(2)} - l_{1}^{(1)}| < w_{HD} \quad \text{and} \quad |l_{2}^{(2)} - l_{2}^{(1)}| < w_{HD},
\]

where \(w_{HD}\) is the width of the boundary elements employed to discretize the horizontal cracks \(HD^+\). If the condition is not satisfied, steps 3 and 4 are repeated using the values \(l_{1}^{(k)}, l_{2}^{(k)}\) to recalculate the stress release induced at the interface by the three interacting cracks. Once the new values \(l_{1}^{(k)}, l_{2}^{(k)}\) are obtained, the test is repeated. When, after \(k\) steps, the test is satisfied, the values \(l_{1}^{(k)}, l_{2}^{(k)}\) represent the final estimates for the positions of \(HD\) crack tips.

4 MODELLING OF THE UNWELDING PROCESS: COMPARISON BETWEEN METHOD I AND METHOD II

In Fig. 5, we compare the two approaches for three different configurations: (a) \(d = 100\) m, (b) \(d = 10\) m and (c) \(d = 0\) m, where \(d \geq z_0 - H\) represents the distance of the upper tip of the MF from the interface between the shallow layer and the half-space (Fig. 3).

As expected, if the MF is sufficiently distant from the interface (Fig. 5a), the results obtained according to Methods I and II are similar, since the back-interaction is low and then might be safely neglected. When the MF is very close to the interface (Fig. 5b), the interaction between the three cracks becomes higher and the slip distributions calculated with the two different methods differ slightly but show similar profiles. The discrepancy increases if a shorter distance \(d\) is considered, but only when the upper tip of the MF touches the interface and the results obtained with the two methods differ substantially, as shown in Fig. 5(c). The crack slip estimated with Method II describes a special case of fault branching in which the main fault merges with the horizontal cracks along the interface. In the following, we shall use the term ‘complete unwelding’ to refer to such a process.

To gain a more detailed view of the system behaviour, the results illustrated in Fig. 5 are reported in Fig. 6 to enable the direct comparison between Methods I and II for each of the three configurations considered. When the MF is distant from the interface (Fig. 6a), the results of the two methods coincide and we can observe that the unwelding at the interface affects two disconnected areas, where the estimated maximum slip on \(HD^\pm\) (\(\sim 0.2\) m) is small with respect to the average slip (\(\sim 2.5\) m) of the MF.

If the MF is closer but at a finite distance from the interface (Fig. 6b), the interaction between the three cracks remains moderate since Method I underestimates the slip obtained using Method II but the slip profiles are very similar, apart for a widening of the unwelded region which is predicted by Method II. The unwelded region at the interface appears as a single item which ranges from \(-l_1\) to \(l_2\) (with \(l_2 \approx 700\) m) and the horizontal dislocations \(HD^\pm\) are closed in \(x = 0, z = H\).

When the MF reaches the interface (Fig. 6c), Method I is unable to model the process of complete unwelding since, in this approach, the MF remains closed at its upper tip. Instead, when back-interaction is taken into account, according to Method II, the slip on \(HD^\pm\) merges continuously with the MF slip and the MF remains open at the interface. Therefore, Method II is able to model in the appropriate way the process of fault branching and layer unwelding.

5 RESULTS AND DISCUSSION

In this section, we perform a parametric study to evaluate how each parameter affects the behaviour of the system. According to the discussion about the two approaches presented in the previous section, in the following we shall refer only to Method II.

In this paper, we do not focus our attention onto a specific rupture zone associated with a particular faulting event. However, to perform computations, it is necessary to fix the parameters using a set of values pertinent to a realistic geodynamical context and compatible with a major strike-slip faulting event. According to these considerations, to describe the properties of the shallower crustal layers, we use the set of values used by Belardinelli et al. (2000) to describe the main features of the SISZ.

\[
m = \mu_2 / \mu_1 = 3 \quad \text{with} \quad \mu_2 = 10 \text{ GPa}, \quad \nu = 0.25, \quad H \sim 500 \text{ m}
\]

\[
\rho(z) = \begin{cases} 
\rho_1 = 2300 \text{ kg m}^{-3}, & \text{if } z < H \\
\rho_2 = 2600 \text{ kg m}^{-3}, & \text{if } z > H
\end{cases}
\]

\[
p(z) = \rho_0 g z \quad \text{(hydrostatic pore pressure)}
\]

and we consider as reference strike-slip faulting event, the one associated with the 1912 Selsund earthquake in the SISZ. The MF parameters are fixed according to the values found by Bjarnason et al. (1993), apart for the depth of the deeper MF tip that later studies suggest to shift from 15 to 12 km. The estimated average slip of \(\sim 2-3\) m for the main structure at depth is reproduced using a value of 2 MPa for the MF stress drop.

The unwelding of the interface is studied in terms of the following parameters:

1. \(d = z_0 - H\), distance of the MF from the interface,
2. \(f\), friction coefficient and
3. \(H\), depth of the interface.

The unwelded region shows very different features considering plausible bounds for the parameter domain and we study how each
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Figure 5. Crack slip on the MF and on $HD^+, HD^-$. The horizontal dislocations $HD^+$ and $HD^-$ have the same orientation and so their slip have opposite signs. The system is antisymmetric with respect to the plane $x = 0$, therefore the two walls of the MF slip in opposite directions with equal magnitude $\Delta u/2$. The stress drop over the MF is $\Delta \sigma = 2$ MPa, the depth of the interface is equal to $H = 400$ m and the rigidity contrast is $m = 3$.

5.1 Dependence on the parameter $d$

If the MF is sufficiently far from the interface, the unwelding condition $|\sigma_{xz}| \geq f(\rho_1 - \rho_w)gH$ is never satisfied and the interface remains welded. While decreasing $d$, the equality condition individual parameter affects the process of unwelding. The unwelding at the interface also determines a redistribution of the stress release and the parametric study can be useful to identify which configurations may be compatible with the typical features observed in strike-slip rupture zones.
Figure 6. Comparison between the results obtained with Methods I (red lines) and II (green): (a) slip curves obtained with either methods overlap when $d = 100\,\text{m}$, and $HD^+$ is clearly disconnected from $HD^-$. When $d = 10\,\text{m}$ (b), $HD^+, HD^-$ become connected and the slip profiles estimated by Methods I and II are mostly similar. According to Method II, when $d = 0\,\text{m}$ the slip of the MF does not vanish at the upper tip [left-side panel of (c)], but merges continuously with the relative slip of the unwelded sections $HD^+$ [right-side panel of (c)].
is first met when \( d = d_0(f, H) \) and then unwelding takes place when the MF gets closer than \( d_0 \) to the interface. In Figs 5 and 6, we show how the slip of the interacting cracks is affected by the distance \( d \) of the MF from the interface. As the MF approaches the interface, the slip of the horizontal cracks increases but complete unwelding takes place only if the MF arrives at the interface. In Fig. 7, the unwelded region \( HD^\perp \) is studied in terms of the model parameters. As the MF gets closer to the interface, \( l_1 \) and \( l_2 \) move in opposite directions, since \( l_1 \) decreases towards \( x = 0 \) whereas \( l_2 \) increases. The trends of \( l_1 \) and \( l_2 \) versus \( d \) are mostly symmetric, apart when the MF arrives close to the interface. Indeed, when \( d \) goes to 0, \( l_1 \) is already \( \sim 0 \) whereas \( l_2 \) increases very rapidly, and the extent \( w = l_2 - l_1 \) of the unwelded region increases sharply.

In Fig. 8, we show the CFF (computed on the optimally oriented plane) and the MOS (computed on the maximum principal plane) relative to three different distances \( d \) of the MF from the interface: \( d = 100 \, \text{m} \) (a), \( d = 10 \, \text{m} \) (b), \( d = 0 \, \text{m} \) (c). These results take into account the effect of back-interaction and correspond to the crack slips displayed in the right column of Fig. 5. Figs 8(a) and (b) show very high values for both the CFF and the MOS in a wide region below the interface. The MF is a finite distance from the interface and no large slip is induced along the interface (Figs 5a and b). Thus, the high values observed for the CFF and MOS can be ascribed mostly to the singular stress released by the MF. These results would suggest the opening of tensile fractures at depths between \( \approx 400 \) and \( \approx 600 \, \text{m} \), but similar findings are very difficult to reconcile with observations. Moreover, there would be no reason for the MF to stop in this configuration, since no friction would be present above its upper tip. Instead, when complete unwelding takes place \((d = 0 \, \text{m}, \text{Fig. 8c})\), the region below the interface is completely relaxed and above the unwelded region a mild stress concentration is observed. Thus, the slip of subordinate shear fractures and the opening of tensile fractures are favoured only in the shallow layer above the area where complete unwelding takes place. In the next section, we shall study in which way the width of this region and the depth at which the secondary fractures may develop are controlled by the other two model parameters \( f \) and \( H \).

5.2 Dependence on the parameters \( f \) and \( H \) when \( d = 0 \, \text{m} \)

In the following, we consider the case of complete unwelding \((d = 0 \, \text{m})\). The width \( 2w \) of the unwelded region is dependent from both \( f \) and \( H \). In Fig. 9, we show \( w \) as a function of \( f \) in the range, \( 0.2 < f < 1 \) for three different depths of the interface \((H = 400 \, \text{m}, H = 600 \, \text{m} \) and \( H = 800 \, \text{m}\)). The increase of the coefficient of friction determines a higher frictional threshold and our results show a narrowing of the unwelded region for larger values of \( f \). The trend of \( w \) as a function of \( f \) is always represented by a smooth curve and the decrease of \( H \) generally determines higher values of \( w \), due to the lower effective pressure \((|\sigma_{zz}| - p)\). However, when \( f \) is extremely small, the free surface condition \( \sigma_{zz} \rightarrow 0 \) in \( z = 0 \) may provide lower \( w \) for lower \( H \).

The role of the parameter \( f \) is illustrated in Fig. 10, where a shallow layer of thickness \( 600 \, \text{m} \) is considered and three reference values of the coefficient of friction, \( f = 0.4 \) (a), \( f = 0.6 \) (b), \( f = 0.85 \) (c), are used to compute the CFF and the MOS. The increase of the coefficient of friction determines a significant shortening of the unwelded region and a considerable increase of the CFF just above the unwelded region, whereas the CFF near the surface and the MOS are not significantly affected. The narrowing of the unwelded region determines a higher concentration of deviatoric stress on top of it and therefore it implies higher values of the CFF. Instead, no significant change of the isotropic stress component is produced and therefore the MOS shows almost the same trend in Figs 10(a)–(c).

The results obtained indicate that open tensile fractures are expected to develop only near the free surface down to depth dependent from the value assumed for the tensile strength of surficial rocks (a few MPa, typically). Instead secondary shear fractures can develop not only below the free surface, but also above the unwelded interface. Also in this case the depth and the extent of these subordinate shear fractures are dependent from the assumed rock strength value.
In Fig. 11, we study the dependence of the CFF and the MOS on the depth $H$ of the interface. The coefficient of friction is fixed to the value $f = 0.4$, whereas three different positions of the interface are considered: $H = 400$ m (a), $H = 600$ m (b), $H = 800$ m (c). In this case, the CFF and the MOS are both significantly affected by the parameter $H$. For the CFF, we observe an almost uniform trend if the interface is closer to the free surface (Fig. 11a). For higher values of $H$ (Figs 11b and c), the stress concentration remains...
confined in the region above the unwelded interface and so at the free surface lower CFF values are obtained. The dependence of the MOS on the parameter $H$ can be explained with the same arguments. If the unwelded region is close to the free surface (Fig. 11a), the redistribution of stress determined by unwelding of the interface increases the MOS in the region close to the free surface. Instead, if the interface is deeper (Fig. 11c), the unwelding cannot provide a significant contribution to the MOS, since the confining pressure increases linearly with depth and so it becomes rapidly the dominant term.

6 CONCLUSIONS

Major strike-slip earthquakes are often associated with a complex pattern of surface fractures, organized in hierarchic order (en-echelon shear fracture arrays, open tensile fractures and hillocks), which are oriented differently from the main fault and often extend laterally a few kilometres, typically more than accurately located surface complexities typically extend only 1–2 km laterally from the main fault strike. In the SISZ (e.g. Stefansson et al. 2011), this assumption may be corroborated by a simple computation: the shear stress created by tectonic motions ($2 \text{ cm yr}^{-1}$), during a seismic cycle $\sim 140 \text{ yr}$, across the $15 \text{ km}$ wide E–W trending seismic zone, is typically much less than 1 MPa in a shallow layer (with rigidity $\mu = 3 \text{ GPa}$), whereas the stress produced in the shallow layer by the main fault is estimated by us as $\sim 5 \text{ MPa}$. Nevertheless, if the regional stress before the earthquake was already close to failure even in the shallow layer, its role may be important in governing the orientation of secondary fractures, which should be classified as triggered aftershocks. Moreover, lateral heterogeneities of rock properties might be invoked, in principle, to explain surface complexities; however, in the SISZ secondary fractures are found after most large earthquakes, which take place over $70 \text{ km}$ from E to W, and they appear evenly distributed along the NS strike of each major fault, showing that lateral heterogeneities should not be significant.

Finally, the present model describes the stress redistribution following unwelding of the interface but it cannot predict in which cases the main fault stops at depth, instead of breaking up to the ground surface. A preliminary asymptotic study has been performed, concerning the change of the stress singularity arising in connection with bending and branching of a strike-slip fault crossing an elastic interface. In the future, we plan to study fault bending and branching employing an energetic criterion for fracture propagation, to see how weak the interface must be in order that the fault does not propagate directly across the soft shallow layer. A similar model was recently addressed by Maccaferri et al. (2010, 2011) for tensile cracks, (describing magmatic dykes deviating horizontally to become sills along a layer interface) and might be adapted to describe the upward propagation of a strike-slip fault.

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Figure 10. CFF and MOS computed in case of complete unwelding ($d = 0$) for (a) $f = 0.4$, (b) $f = 0.6$ and (c) $f = 0.85$. Interval between level lines 1 MPa. Layer thickness $H = 600$ m.
Figure 11. CFF and MOS computed in case of complete unwelding (d = 0) for (a) H = 400 m, (b) H = 600 m and (c) H = 800 m. Interval between level lines 1 MPa. Friction coefficient $f = 0.4$. 
REFERENCES

APPENDIX A: STRESS COMPONENTS INDUCED BY VERTICAL AND HORIZONTAL STRIKE-SLIP DISLOCATIONS

The stress components $\sigma_{ij}$ induced at the observation point $P(x, z)$ (1, layer 2, half-space) by a vertical strike-slip dislocation, opening with unit Burgers vector in direction y along the dislocation line $(x = x_l, z = z_0)$ parallel to the $y$-axes and embedded in the half-space ($H$), are computed from the displacement field (Rybicki 1971) and are reported below:

$$\begin{align*}
(\sigma_{ij})_{ij} &= -\frac{\mu_1}{2\pi} \frac{2m}{1 + m} \sum_{n=0}^{\infty} \Gamma^n \left[ \frac{\frac{z - z_0 + 2nH}{U^2_n} - \frac{z + z_0 + 2nH}{W^2_n}}{U^2_n} \right],
\end{align*}$$

(A1)

$$\begin{align*}
(\sigma_{ij})_{iy} &= \frac{\mu_1}{2\pi} \frac{2m}{1 + m} (x - x_0) \sum_{n=0}^{\infty} \Gamma^n \left[ \frac{1}{U^2_n} - \frac{1}{W^2_n} \right],
\end{align*}$$

(A2)

$$\begin{align*}
(\sigma_{ij})_{iz} &= \frac{\mu_1}{2\pi} \frac{2m}{1 + m} (x - x_0) \sum_{n=0}^{\infty} \Gamma^n \left[ \frac{1}{U^2_n} - \frac{1}{W^2_n} \right],
\end{align*}$$

(A3)

$$\begin{align*}
(\sigma_{ij})_{22} &= \frac{\mu_2}{2\pi} \frac{2m}{1 + m} \left( \frac{z - z_0}{U^2_0} + \frac{z + z_0 + 2H}{U^2_0} \right) + \frac{z + z_0 + 2H}{T^2_0} - \frac{4m}{1 + m} \sum_{n=0}^{\infty} \Gamma^n \frac{z + z_0 + 2nH}{W^2_n}.
\end{align*}$$

(A4)

where $m$, $\Gamma$, $r_i'$, $s'_i$, $T_n$, $U_n$, $W_n$ are defined at the end of this Appendix. A dislocation element of the main fault, extending from $z_1 - \frac{H}{2}$ to $z_1 + \frac{H}{2}$, is obtained taking the difference of the previous formulae computed for $z_0 = z_1 = \pm \frac{H}{2}$ and $z_0 = 0$. The influence coefficient $A_{ij}^{(z_0)}$ is the stress component $\sigma_{ij}$ computed in $x = 0$, $z = z_0$, due to the dislocation element centred in $z_0$. The influence coefficient $A_{ij}^{(z_0)}$, is the stress component $\sigma_{ij}$ computed in $z = H, x = x_0$, due to the dislocation element centred in $z_0$ (and similarly for $A_{ij}^{(z_0)}$).

The same notation is adopted considering the stress in layer 1 or 2 due to a horizontal strike-slip dislocation in layer 1, opening over the half-plane $z = z_0, x > x_0$ in the upper layer ($z_0 \leq H$, Singh & Rani 1994).

$$\begin{align*}
(\sigma_{ij})_{1i} &= -\frac{\mu_1}{2\pi} \frac{2m}{1 + m} \left( \frac{z - z_0}{U^2_0} - \frac{z + z_0}{T^2_0} \right) + \frac{z + z_0}{W^2_0} + \sum_{n=1}^{\infty} \Gamma^n \left[ \frac{s_i'}{U^2_n} + \frac{s_i'}{T^2_n} - \frac{s_i'}{W^2_n} \right],
\end{align*}$$

(A5)

$$\begin{align*}
(\sigma_{ij})_{1y} &= \frac{\mu_1}{2\pi} \frac{2m}{1 + m} \left( \frac{1}{U^2_0} - \frac{1}{T^2_0} + \sum_{n=1}^{\infty} \Gamma^n \left[ -\frac{1}{T^2_n} + \frac{1}{U^2_n} - \frac{1}{W^2_n} \right] \right),
\end{align*}$$

(A6)

$$\begin{align*}
(\sigma_{ij})_{2i} &= \frac{\mu_2}{2\pi} \frac{2m}{1 + m} \left( \frac{z - z_0}{U^2_0} - \frac{z + z_0}{T^2_0} + \sum_{n=1}^{\infty} \Gamma^n \left[ \frac{s_i'}{U^2_n} - \frac{s_i'}{W^2_n} \right] \right),
\end{align*}$$

(A7)

$$\begin{align*}
(\sigma_{ij})_{2y} &= \frac{\mu_2}{2\pi} \frac{2m}{1 + m} \left( \frac{1}{U^2_0} - \frac{1}{T^2_0} + \sum_{n=1}^{\infty} \Gamma^n \left[ \frac{1}{U^2_n} - \frac{1}{T^2_n} \right] \right).
\end{align*}$$

(A8)

In this case, a horizontal dislocation element from $x_1 - \frac{H}{2}$ to $x_1 + \frac{H}{2}$ over the interface is obtained taking the difference of the previous formulae computed for $x_0 = x_1 = \pm \frac{H}{2}$ and $z_0 = H$. The influence coefficient $A_{ij}^{(z_0)}$ is the stress component $\sigma_{ij}$ computed in $x = x_1, z = H$, due to the dislocation element of $HD^+$ centred in $x_1$. The influence coefficient $A_{ij}^{(z_0)}$ is the stress component $\sigma_{ij}$ computed in $x = x_1, z = H$, due to the dislocation element of $HD^-$ centred in $x_1$ (and similarly for the other influence coefficients).

All symbols employed in this Appendix are defined below:

$$\begin{align*}
m &= \frac{\mu_2}{\mu_1}, \quad \Gamma = \frac{1 - m}{1 + m},
\end{align*}$$

$$\begin{align*}
&\begin{cases}
 r'_i = z - z_0 - 2nH, \quad s'_i = z - z_0 + 2nH \\
n'_s = z + z_0 + 2nH, \quad s''_i = z + z_0 - 2nH \\
T_n^2 = (x - x_0)^2 + (z - z_0 - 2nH)^2 \\
U_n^2 = (x - x_0)^2 + (z - z_0 + 2nH)^2 \\
V_n^2 = (x - x_0)^2 + (z + z_0 + 2nH)^2 \\
W_n^2 = (x - x_0)^2 + (z + z_0 + 2nH)^2
\end{cases}
\end{align*}$$

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