Efficient Inversions for Earthquake Slip Distributions in 3D Structures
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ABSTRACT
Advances in observational and computational seismology in the past two decades have made it possible for fully automatic and real-time determinations of the focal mechanisms of point earthquake sources. However, sources of all large and small earthquakes are intrinsically finite and heterogeneous, both temporally as well as spatially. Therefore, a full picture of the source slip distribution is essential not only for a better understanding of earthquake physics but also for accurate account of the source directivity effect for reliable and realistic predictions of earthquake-induced strong ground motions. We develop a source inversion technique that combines a well-established slip-distribution inversion method and an efficient algorithm for computing accurate synthetics in 3D structures based on a pre-established strain Green tensor database. This new technique makes it practical for slip-distribution inversion in 3D structures, which not only enhances the capability of resolving source slip distributions of moderate earthquakes through better accounting of the effects of lateral structural heterogeneities but also provides an effective tool for the development of automatic systems for near-real-time inversions of earthquake source slip distributions for seismic-hazard mitigation purposes.

Online Material: Figures of station and event locations, velocity models, and waveform comparisons.

INTRODUCTION
Understanding of earthquake source physics requires a good resolution of the source process, which can be fully defined by the distribution of slip function on a finite-fault plane and in a finite duration in time. Techniques for the inversion of slip distributions of finite-earthquake sources using seismic records have been developed and applied to large earthquakes for several decades (e.g., Kikuchi and Kanamori, 1982; Olson and Apsel, 1982; Hartzell and Heaton, 1983; Ji et al., 2002; Minson et al., 2013). Efficient algorithms have also been developed for rapid imaging of earthquake sources in 1D Earth models (e.g., Dreger and Kaverina, 2000; Ji et al., 2004; Zhang et al., 2014, 2015). Detailed mapping of spatial and temporal distributions of slip on the fault plane provides a direct resolution to the earthquake source kinematic characteristics and rupture propagation, which are important for the seismic-hazard assessments through physics-based simulations of wavefields, in addition to ground-motion prediction equations (e.g., Abrahamson and Silva, 2008; Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008; Baumann and Dalguer, 2014). Thus, reliable slip-distribution models of large and moderate earthquakes are not only important for academic interests but also have strong social impacts.

Conventional finite-fault inversion schemes are mostly based on linearized inversion approach, with objective functions defined by the L2-norm errors of waveform misfits. For earthquakes of moderate and large magnitudes ($M_w > 6$), the relatively low-frequency signals (below 0.2 Hz) usually dominate the displacement records. Then, when there is a conflict between the low-frequency signals and high-frequency but smaller amplitude ones, the inversion would attempt to overfit the long-period signals while sacrificing the fits to high-frequency ones. Low-frequency information, while essential to constrain the overall picture of a seismic source, is not as sensitive to the detailed rupture characteristics, such as the variations of rise time or rupture velocity. On the other hand, a sudden change in the slip amplitude or rupture velocity radiates strong high-frequency seismic signals (effects similar to a stopping phase; e.g., Aki and Richards, 1980). Hence, utilizing higher frequency signals in finite-fault inversions can effectively increase the spatial and temporal resolutions.

Ji et al. (2002) adopted a wavelet approach to transform the time-domain waveform into wavelet domain, thus transferring the fitting of the time-domain full waveform into the matching of individual wavelets of different time–frequency contents. Furthermore, by defining different objective functions for wavelets of different frequencies, an optimal multiscale resolution to the source slip distribution is achieved.

Another important factor that influences the resolution of slip-distribution inversion is the effect of lateral variation in the velocity structure. Graves and Wald (2001) examined the difference of source inversions in 1D and 3D models and concluded that an effective 3D structural model can separate the source signals from 3D propagation effects and improve the resolution of slip-distribution inversion. When 3D heterogeneity is not strong and the stations are close to source, the advantage of using
3D synthetic seismograms in source inversions might not be significant. For example, Konca et al. (2013) found that a random 3D structural variation of up to 5% does not lead to significant degradation of the source model. But when 3D heterogeneity is significant, using 3D response shall allow us to use relatively distant records, which often leads to significant improvement in the azimuthal coverage of the source. Slip-distribution inversions performed using 3D structural models are highly preferred if an effective 3D structure model is available. However, it is noteworthy that using 3D models does not necessarily lead to better waveform fitting in source inversions, and careful examination of the results obtained from all available structural models is needed to determine the range of possible fault models (Liu and Archuleta, 2004).

In this study, we develop a source inversion technique by taking advantage of the slip-distribution inversion method of Ji et al. (2002, 2003) and the efficient approach to calculating accurate 3D synthetics based on the pre-established strain Green tensor (SGT) database (Zhao et al., 2006). This new approach allows for efficient slip-distribution inversions in 3D structures, which not only enhances the capability of resolving source slip distributions of moderate earthquakes but also provides an effective tool for near-real-time inversions of earthquake source slip distributions.

**SLIP-DISTRIBUTION INVERSION IN 3D STRUCTURAL MODELS**

When the finiteness of the earthquake source is considered, the linearity of the seismic-wave equation allows us to divide the finite source into a set of subfaults, each of which is considered as a spatially point source with its own time history (Fig. 1), and model the total response in terms of the superposition of the responses from all individual subfaults

\[
u_s(t) = \sum_{\beta=1}^{N} \sum_{\alpha=1}^{M} \mu^{\alpha\beta} S^{\alpha\beta} A^{\alpha}(t, V^{\alpha\beta})
+ \sin(\lambda^{\alpha\beta}) V^{\alpha\beta}(t, V^{\alpha\beta}) \right] h^{\alpha\beta}(t)
\]

(Ji et al., 2003), in which \(u_s(t)\) is the \(n\)-component displacement field at the station, and the \(\alpha\) and \(\beta\) are respectively the along-strike and down-dip indexes of subfault \((\alpha, \beta)\) with area \(A^{\alpha\beta}\) and rigidity \(\mu^{\alpha\beta}\), respectively. \(S^{\alpha\beta}\) and \(\lambda^{\alpha\beta}\) are the amount and rake angle of slip on the subfault, respectively, and \(h^{\alpha\beta}(t)\) is the normalized asymmetric slip-rate function defined as

\[
h^{\alpha\beta}(t) = \begin{cases} 
\frac{1}{\tau_{s}^{\alpha\beta}} \left[ 1 - \cos\left( \frac{\tau_{s}^{\alpha\beta}}{\tau_{e}^{\alpha\beta}} \right) \right], & 0 < t < \tau_{s}^{\alpha\beta} \\
\frac{1}{\tau_{e}^{\alpha\beta}} \left[ 1 - \cos\left( \frac{\tau_{s}^{\alpha\beta} - t}{\tau_{e}^{\alpha\beta}} \right) \right], & \tau_{s}^{\alpha\beta} < t < \tau_{e}^{\alpha\beta}, \\
0, & t > \tau_{e}^{\alpha\beta}
\end{cases}
\]

(Fig. 1) for several different values of starting- and end-phase times. \(V^{\alpha\beta}\) in equation (1) is the rupture speed be-

![Figure 1. Parameterization in (a) space and (b) time of the slip-distribution models of finite-earthquake sources. The fault plane is divided by a uniform grid into \(M \times N\) subfaults. The hypocenter, indicated by the gray star, is located in subfault \((\alpha_s, \beta_s)\). An arbitrary subfault \((\alpha, \beta)\) can be defined by five source parameters: the amount and rake angle of slip \(S^{\alpha\beta}\) and \(\lambda^{\alpha\beta}\), respectively, the rupture speed from the hypocenter \(V^{\alpha\beta}\), and the starting- and end-phase times \(\tau_{s}^{\alpha\beta}\) and \(\tau_{e}^{\alpha\beta}\), respectively, of the normalized asymmetric slip-rate function.](image-url)
between the hypocenter and the subfault, which controls the rupture initiation time of subfault \((\alpha, \beta)\). \(X^{\alpha \beta}(t, V^{\alpha \beta})\) and \(Y^{\alpha \beta}(t, V^{\alpha \beta})\) are the Green’s functions representing the \(n\)-component displacements at the station from unit along-strike and down-dip slips, respectively.

In equation (1), the Green’s functions \(X^{\alpha \beta}\) and \(Y^{\alpha \beta}\) can be calculated in either 1D or 3D models for finite-fault inversion. Green’s functions calculated in 1D structural models, due to their efficiency, have been used for decades in slip-distribution inversions. Here, we adopt the SGT database approach (Zhao et al., 2006; Hsien et al., 2014), which enables rapid calculations of accurate synthetics for slip-distribution inversions in 3D structural models with realistic surface topography.

The SGT is based on the definition of the Green tensor \(G(r_0, t; r_s)\) for the seismic-wave equation, through which the \(n\)-component displacement \(u_n\) at an arbitrary location \(r\) from a point source at \(r_s\) with a moment tensor \(M\) can be expressed as

\[ u_n(r, t; r_s) = \sum_{j=1}^{3} \sum_{k=1}^{3} M_{jk} G_{jn}(r, t; r_s), \tag{3} \]

(e.g., Aki and Richards, 1980), in which the superscript \(S\) indicates that the differentiation operator acts on the source coordinates \(r_s\). Zhao et al. (2006) introduced the third-order SGT from the source at \(r_s\) to the receiver at \(r\)

\[ H_{jkn}(r, t; r_s) = \frac{1}{2} \left[ \partial_{j} G_{kn}(r, t; r_s) + \partial_{k} G_{jn}(r, t; r_s) \right], \tag{4} \]

which has the symmetry property

\[ H_{jkn}(r, t; r_s) = H_{jnk}^{*}(r, t; r_s). \tag{5} \]

Taking advantage of the reciprocity property of the Green tensor

\[ G_{ij}(r, t; r_s) = G_{ji}(r_s, t; r), \tag{6} \]

(e.g., Aki and Richards, 1980; Dahlen and Tromp, 1998), the displacement in equation (3) can be expressed in terms of the SGT

\[ u_n(r, t; r_s) = \sum_{j=1}^{3} \sum_{k=1}^{3} M_{jk} H_{jkn}(r_s, t; r) = M : H(r_s, t; r) \tag{7} \]

(Zhao et al., 2006; Zhao and Chevrot, 2011), in which the displacement at \(r\) due to an earthquake at \(r_s\), \(u(r, t; r_s)\) has been expressed in terms of the SGT from the receiver to the source \(H(r_s, t; r)\). Thus, as depicted in Figure 2, for a given seismic station located at the known location \(r = r_s\), the response \(u(r_s, t; r_s)\) can be obtained via equation (7) using the SGT for the station \(H(r_s, t; r_s)\), as defined in equation (4). By running three numerical simulations for three orthogonal unit-impulsive point forces acting at the station location \(r_s\), we can obtain \(H(r_s, t; r_s)\), the SGT from \(r_s\) to all the grid points in a 3D model with realistic topography. We can run the simulations for all available stations and save the SGTs on the disk. With the help of such a pre-established SGT database, the displacement at each station from any source location in the computational volume can be evaluated by simply retrieving from

\[ \text{Figure 2. Schematic diagram illustrating two ways to express the seismic response at a station } r_s \text{ from an earthquake at } r_s \text{ in a 3D velocity model with surface topography. After an earthquake, the seismic response } u(r_s, t; r_s) \text{ can be obtained by a numerical simulation from } r_s, \text{ which takes a few tens to hundreds of minutes depending on the available hardware. Although we used a pre-established strain Green tensor (SGT) database for the station at } r_s, \text{ the same response can be obtained via equation (7) in less than a second by simply retrieving } H(r_s, t; r_s) \text{ from the database.} \]

\[ \text{Figure 3. Configuration of a finite-fault plane in central Taiwan and 32 randomly distributed stations used in the synthetic test. The fault plane has a strike of 45° and a dip of 60°, with its center being the hypocenter of the earthquakes in the tests. Blue line traces the fault on the surface. The stations are all on land and within 150 km from the hypocenter. The red box in the inset map shows the area for the main figure.} \]
the database the SGT corresponding to the specific source and station locations and by multiplying the corresponding SGT and moment tensor elements following equation (1). This SGT database approach enables us to rapidly compute accurate synthetics at many stations from any source location in a realistic 3D model with surface topography. It has been successfully applied to the inversion of the focal mechanisms of point earthquake sources (Chao et al., 2011; Lee et al., 2011) and finite-moment tensor (FMT; e.g., Bukchin, 1995; McGuire et al., 2001; Chen et al., 2005) solutions of moderate earthquakes in Taiwan (Hsieh et al., 2014).

In the calculation of synthetics of a finite-earthquake source as expressed in equation (1), the Green’s functions corresponding to the unit along-strike and down-dip slips on each subfault \( S^{αβ}(t, V^{αβ}) \) and \( Y^{αβ}(t, V^{αβ}) \), respectively, are obtained from the SGTs retrieved from the database. Their dependence on the rupture speed \( V^{αβ} \) is due to the fact that they are both delayed in time by \( t_0^{αβ} = \frac{p_α}{p_β}V^{αβ} \). Thus, each subfault can be fully represented by five variables: \( S^{αβ}, X^{αβ}, Y^{αβ}, \tau^{αβ}, \) and \( \tau^{αβ}_e \), which amount to a total of \( S \times M \times N \) model parameters for the entire fault plane to be determined in the inversion for the slip distribution of a finite-earthquake source.

In this study, we adopt the approach of Ji et al. (2002, 2003) in the implementation of earthquake source slip-distribution inversions in 3D models. Compared with other well-established source inversion techniques, the method of Ji et al. (2002) has two important distinguishing characteristics: a wavelet decomposition of the time-domain waveforms and a nonlinear search of the optimal slip-distribution parameters based on the simulated-annealing (SA) algorithm. Wavelet analysis enables optimal extraction and resolution of the frequency–time mixed information carried in the seismic waveforms. Furthermore, Ji et al. (2002) imposed different criteria in fitting the waveforms of different frequencies. To alleviate the problem of results being dominated by long-period waves of relatively large amplitudes commonly encountered in waveform inversion, the objective function for the wavelet coefficients of longer-period wavelets is defined in terms of both L1 and L2 norms, whereas for shorter-period wavelets the objective function is defined by the correlation function of the wavelet coefficients. The optimal solution for the slip-distribution model that minimizes the total objective function is found through a nonlinear search in the model space based on the SA algorithm (Rothman, 1986; Sen and Stoffa, 1991, 1995).

SYNTHETIC TESTS

The slip-distribution inversion technique of Ji et al. (2002) has been adopted by the U.S. Geological Survey (USGS) in its routine inversions of large earthquakes \( (M_w \geq 7.0) \) using a 1D velocity model and broadband waveforms at teleseismic distances. Here, we use the SGT database approach to extend the capability of this technique so that 3D models can be used to provide more accurate synthetics, which enables us to invert for source slip distributions of moderate earthquakes \( (M_w \sim 6.5) \) using regional broadband seismic records.

Before applying our approach to the seismic records from real earthquakes, we first conduct synthetic tests to validate the slip-distribution inversion results. For the synthetic tests, we use a fault plane placed in central Taiwan with a 45° strike and a 60° dip, and a total of 32 sites are randomly selected within 150 km from the center of the fault plane, as shown in Figure 3. These 32 sites serve as fictitious stations providing good coverage in both azimuth and in epicentral distance. The fault plane

\[ \text{Figure 4. (a) One-subfault source model and (b) three-subfault source model used as input source models in slip-distribution inversion tests.} \]

The total moment for the one-subfault model in (a) is \( 1 \times 10^{25} \) dyn·cm distributed on the single subfault. For the three-subfault model in (b), the moments are \( 1 \times 10^{22} \) dyn·cm each on the two shallower subfaults but \( 2 \times 10^{22} \) dyn·cm on the deeper subfault, resulting in a total moment of \( 4 \times 10^{22} \) dyn·cm. Colors indicate the amount of slip on the subfaults (a: 231.7 cm; b: 344.8 cm, 231.7 cm, and 378.0 cm from top to bottom subfault, respectively), whereas black arrows depict the rake angles (a: 60°; b: 30°, 60°, and 90° from top to bottom subfaults, respectively). Contours represent rupture time \( t_0^{αβ} = \frac{p_α}{p_β}V^{αβ} \). (c) The rigidity values on the fault plane in the model used in generating the synthetic data for the tests. The white stars in the center of the fault plane denote the hypocenter.
is divided into 11 segments in both along-strike and down-dip directions, and each subfault has an area of $3.33 \times 3.33$ km$^2$.

For slip-distribution inversion, we first establish the SGT database for the 32 fictitious stations using a recent regional tomography model for Taiwan (Kuo-Chen et al., 2012) and the ETOP01 digital terrain model (Amante and Eakins, 2009) for surface topography. The SGTs are calculated by the finite-difference algorithm of Zhang and Chen (2006) and Zhang et al. (2012), which accommodates accurately the topography on the free surface as well as on the interfaces in the structural model. The establishment of SGT database itself involves numerical simulations of wave propagation in 3D structure, which still require considerable parallel computation, depending on the frequency content needed for the synthetics and the number of stations used. In this study, the horizontal grid spacing is 2.4 km, whereas vertically the grid spacing varies from 0.857 km near the surface to 3.913 km at 40 km depth. For the simulation from each station, the SGT results on grid points in a volume surrounding the fault plane are saved on a hard disk. With this database, synthetics at all stations from any possible point on the fault plane can be evaluated via equation (7) in merely a few seconds, thus making it practical to quickly invert for source slip distributions in 3D structure.

We consider two source models in the synthetic tests (Fig. 4), a point source represented by only one subfault and a finite source involving three subfaults with different rake angles and rupture times. Synthetic seismograms in the 3D model at the 32 fictitious stations are computed with the help of the SGT database, are low-pass filtered with a 0.8-Hz cutoff frequency, and serve as data in the slip-distribution inversion tests. In addition to validate the algorithm, we examine the influence of the structural heterogeneity on the fault plane by considering two different rigidity ($\mu_{\alpha\beta}$ in equation 1) models in slip-distribution inversions: a heterogeneous rigidity (Fig. 4c) fault plane on which the rigidity values $\mu_{\alpha\beta}$ are retrieved from the same 3D velocity model used to obtain the data and a rigidity model with a uniform value of $3 \times 10^{11}$ dyn/cm$^2$ on all subfaults.

The slip-distribution inversion results for the point-source model are displayed in Figure 5. In the recovered source models

![Figure 5. Results from slip-distribution inversion tests for the one-subfault source model in Figure 4a for two rigidity models: (a) recovered slip distribution (236.1 cm and 60°) when the same heterogeneous rigidity model (d, the same model as in Fig. 4c) used to compute synthetic data is also used in the inversion; and (b) recovered slip distribution (305.7 cm and 60°) when a constant rigidity model (e) is used in the inversion. The white stars in the middle of the fault plane indicate the hypocenter. In (a) and (b), contours depict rupture times at individual subfaults, and colors indicate the amount of slip on the subfaults from inversion. (c) Moment rate functions. Black is the input model, whereas red and blue are for recovered models in (a) and (b), respectively.](image-url)
using both variable and uniform rigidity on the fault plane, the slips are concentrated on the correct subfault with minimum smearing. The slip angles in the inversion results are the same as the input values. However, the amount of slip at the single subfault shows a value of 236.1 cm from the inversion in the actual variable rigidity model on the fault (Fig. 5a), almost the same as the input, but shows a very different value of 305.7 cm in the constant rigidity model (Fig. 5b), which is incompatible with the actual structure. This is largely due to the different rigidity values at the location of the central subfault in the two different rigidity models (Fig. 5d,e). The recovered moment rate functions (Fig. 5c) are very similar, with small losses of amplitudes and slightly longer tail sections. These results not only confirm the validity of our implementation of the 3D SGT database approach in the source slip-distribution inversion, but also demonstrate the importance of the rigidity model in recovering the right amount of slip.

Figure 6 shows the inversion results for the three-subfault source models with different slips on the subfaults. In the input model, a constant rupture speed of 2.0 km/s has been used in calculating the data. The moment-rate function (black curve in Fig. 6c) from such a rupture speed has three distinct peaks with some overlap in time in the latter two rupturing subfaults. In the recovered models for both rigidity structures, rupture initiates from the central subfault, the hypocentral location, and the slips correctly concentrate on the three subfaults in the input model with minor smearing. The slip angles from the inversions are again very similar to the input values. Likewise, the moment-rate function is also well recovered in both inversions (Fig. 6c). The amount of slip is also nicely recovered for all three subfaults from inversion using the appropriate rigidity model, whereas when using a rigidity model incompatible with the actual structure, the amount of slip is very different from the correct values.

Figure 6. Results from slip-distribution inversion tests for the three-subfault source model in Figure 4b for two rigidity models: (a) recovered slip distribution (slip: 327.7, 240.6, and 341.8 cm from top to bottom subfaults, respectively, and rake: 30°, 60°, and 91°) when the same heterogeneous rigidity model (d, the same model as in Fig. 4c) used to compute synthetic data is also used in the inversion; and (b) recovered slip distribution (slip: 282.8, 310.3, and 542.7 cm from top to bottom subfaults, respectively, and rake: 30°, 60°, and 91°) when a constant rigidity model (e) is used in the inversion. The white stars in the middle of the fault plane indicate the hypocenter. In (a) and (b), contours depict rupture times at individual subfaults, and colors indicate the amount of slip on the subfaults from inversion. (c) Moment rate functions. Black is the input model, whereas red and blue are for recovered models in (a) and (b), respectively.
inversion result. Here, we apply our 3D SGT database approach to the 31 October 2013 earthquake ($M_w$ 6.4) that occurred in Ruisui in southeastern Taiwan, beneath the eastern slope of the Backbone Range.

Figure 7 shows the location of the Ruisui earthquake and focal mechanism solutions from three different agencies. The event was located by the Central Weather Bureau (CWB) of Taiwan at 121.35° E and 23.57° N with a hypocentral depth of 15.0 km. However, the waveform-derived focal mechanisms put the centroid at slightly greater depths. For example, the gCAP (Zhu and Ben-Zion, 2013) solution, which uses regional broadband waveforms from Broadband Array in Taiwan for Seismology (Kao et al., 1998) and Green’s functions calculated in Taiwan’s regional average 1D model, has a centroid depth of 25 km and $M_w$ 6.2; whereas the Global Centroid Moment Tensor solution using long-period teleseismic records yields a centroid depth of 20.1 km and $M_w$ 6.3.

Near-fault strong-motion coverage of this earthquake is also not optimal. Eight stations are located within 50 km of the epicenter (Fig. 7) and all of them are stations under the CWB Taiwan Strong Motion Instrumentation Program (TSMIP). They provide a very narrow azimuthal coverage to the source, from 18° to 35° with respect to the CWB epicenter. The stations on the west side of the Backbone Range then have to be included (Fig. 7), but their epicentral distances are in the 47–122 km range. Waveform records at those stations are strongly affected by the complex 3D velocity structure beneath the Backbone Range as well as its surface topography (see Figs. S1–S3, available in the electronic supplement to this article).

We begin by establishing the 3D SGT database for all the broadband and strong-motion stations we use. The SGTs were calculated for accurate wavefields up to 0.8 Hz in the 3D model of Kuo-Chen et al. (2012) with ETOP01 topography, and results on grid points in a volume surrounding the hypocenter are saved on a hard disk. Using a modest computer cluster with, say, 200 cores, it takes ~3 days of wall-clock time to compute SGTs for all the 17 stations used, and the storage for the SGT database is on the order of tens of gigabytes. Such a database can only be used to study the Ruisui earthquake, because only SGTs in the vicinity of its hypocenter are stored. General-purpose SGT database can be established by storing the SGTs on the grid points in an entire region so that the same database can be used by all possible earthquakes within its coverage.

We then use the two-step approach of Hsieh et al. (2014) to determine the point-source focal mechanism and the average finite-source properties (i.e., FMT) of this event in the 3D model. The focal mechanism (green focal mechanism plot in Fig. 7) and the moment magnitude $M_w$ 6.33 obtained in 3D model are similar to the other solutions, whereas the centroid depth determined in 3D model is 14.4 km, closer to the CWB hypocentral depth but significantly shallower than the other two solutions mentioned above. This centroid depth is in fact consistent with both aftershock distribution and the inverted slip model discussed next, an excellent example for the advantage of using a 3D structural model in finite-fault inversions. Results for the average finite-source properties show

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The regional average 1D model for Taiwan used in the gCAP solution, has a centroid depth of 20.1 km and $M_w$ 6.3. These synthetic tests demonstrate that the precalculated SGT database is crucial to the efficiency in considering 3D structures and topography effects in slip-distribution inversions. In particular, realistic 3D structures not only improve the accuracy in modeling the waveforms, but are also important in the recovery of the correct amount of slip at different locations on the fault plane.

**SLIP-DISTRIBUTION INVERSION FOR THE 2013 RUISUI, TAIWAN, EARTHQUAKE**

At the present time, finite-fault inversions are mostly carried out in 1D models. However, as shown in finite-fault inversion for the 2014 South Napa, California, earthquake (Dreger et al., 2015), there is clearly a need to account for the effect of lateral structural heterogeneity to reduce the uncertainty in the source
that the Ruisui earthquake is a horizontally propagating rupture on the west-dipping nodal plane, with a rupture speed of \( \sim 3.3 \text{ km/s} \) in the northeast direction, opposite to the strike.

Guided by the two-step results for the focal mechanism and average rupture properties, we set up a planar fault plane for inverting the slip distribution of this earthquake. The fault plane is the west-dipping one from the 3D result (strike 197° and dip 42°) and has dimensions of 48 and 30 km along-strike and dip directions, respectively. The fault plane is divided into two distinct regions of slip concentration, that is, asperities, can be seen, with a weaker one located next to the hypocenter and rupturing within the first 3 s, and a much stronger one located further north and rupturing in the next 5 s. The rupture propagates largely horizontally from the hypocenter in north-northeast (NNE) direction, directly opposite to the strike of the fault plane but with a small upward component. The maximum slip of \( \sim 1.2 \text{ m} \) occurs \( \sim 15 \text{ km} \) NNE of the hypocenter. The distribution of the two blobs of higher slip defines a centroid location roughly 15 km northeast of the hypocenter with a 12.4-km centroid depth, in agreement with the centroid location of Lee et al. (2014). Even though the entire rupture lasted for \( \sim 22 \text{ s} \), more than 80% of the moment was released in the first 8 s. The resulting magnitude \( M_w \) 6.4 agrees with results of point-source focal mechanisms. The residual of waveform fitting is 0.2310. For the convenience of further discussion, we hereafter refer to this model as model 3D-3D.

Figure 9a shows the map view of the inverted slip distribution of the model 3D-3D, accompanied with the epicenters of the 1-week aftershocks (blue dots). The distribution of aftershocks includes two separate clusters, which are apparently associated with the rupture of two asperities: a smaller cluster around the small asperity next to the hypocenter and a larger one distributed along the up-dip and northeast vicinity of the large (and also dominant) asperity. A striking feature in the aftershock distribution is that there is hardly any aftershock activity south and west (i.e., below) of the hypocenter, a strong indication that this event is likely a purely unilateral rupture,
almost horizontally in the northeast direction. Slip directions (Fig. 10b) indicate that the earthquake is a combination of thrust and left-lateral strike-slip faulting, with a stronger thrust component on the larger asperity.

For comparison, we also conduct two further experiments to test the sensitivities of the inverted slip-distribution inversion result to the structural model and the focal mechanism solution. In the first experiment, we adopt the same fault plane derived from the moment tensor solution using 3D Green’s functions but invert for the slip distribution using synthetic seismograms calculated in Taiwan’s regional average 1D model (Fig. 7). The solution is hereafter referred to as model 3D-1D (Figs. 9b and 10d). In the second experiment, we use the fault plane inferred from the aforementioned gCAP solution and invert for the fault model using 1D synthetics. The solution is hereafter referred to as model 1D-1D (Figs. 9c and 10f). The waveform-fitting residuals of models 3D-1D and 1D-1D are 0.2403 and 0.2334, respectively, worse than that of model 3D-3D. In the comparisons of the three slip models in Figures 9 and 10, the overall patterns of models 3D-1D and 1D-1D are similar to model 3D-3D: a unilateral rupture propagation in the northeast direction with a major slip zone ~15 km from the hypocenter and a slip dominated by thrust motion with a small left-lateral strike-slip component. The slip distributions obtained from the two 1D inversions are similar, even though their fault planes have different orientations, suggesting that the slip-distribution inversion is stable with an acceptable level of uncertainty in the focal mechanism. However, there are two important discrepancies between the slip distributions obtained in 1D and 3D models. First, both inversions in 1D structure yield lower total seismic moments with the same magnitude of $M_w$ 6.2, which may be due to the scattering of seismic energy by the lateral heterogeneities in the 3D model and by surface topography. Second, the 3D result has two distinct asperities. The large asperity centering ~15 km northeast of the hypocenter can also be seen in models 3D-1D and 1D-1D. However, the smaller asperity near the CWB hypocenter can barely be identified in model 1D-1D (Figs. 9c and 10f) and is nearly entirely blurred out in model 3D-1D (Figs. 9b and 10d). As the coefficient of the Laplace smoothing constraint is fixed in the inversions of all three models presented here, the more compact and therefore higher amplitude image of the small asperity in model 3D-3D can be viewed as a sign of better spatial constraint, presumably due to the use of 3D earth response.

In Figure 10a,b, we also compared the 3D rigidity model with model 3D-3D slip distribution. The slip terminates in the up-dip direction when it reaches the region with low rigidity. Such a relationship has also been widely reported in the studies of other earthquakes (e.g., Mishra et al., 2003).

Finally, we compare in Figure 11 the ground-motion predictions by point and finite sources with the observation. The observed peak ground velocity (PGV) map (Fig. 11b) obtained from the TSMIP stations shows a very clear unilateral rupture propagation with NNE directivity. The PGV map predicted by the slip distribution obtained in 3D model (Fig. 11c) reproduces a very similar pattern to that in the observed map. However, the maximum amplitude is smaller than the observation by a factor of ~2. Two major factors can lead to the theoretical
underestimation of PGV values. First, the source-slip-distribution inversion was performed using waveforms with frequencies below 0.4 Hz. Second, even though we have applied the USGS empirical ground-motion correction factors for site effect (Wald et al., 2005) to our PGV prediction, the site amplification correction is still insufficient, especially in the near field. The PGV map predicted by the point source (Fig. 11a) shows a clear four-lobed radiation pattern with no directivity. The maximum amplitude is more than double the observation, because the seismic energy is emitted impulsively in time, leading to ground motions of higher peak amplitudes but shorter durations.

**CONCLUSIONS**

In this study, we successfully incorporated an SGT database approach into a well-established and robust slip-distribution in-

![Figure 10](image-url). Slip-distribution inversion results for the Ruisui earthquake obtained using different structural models and focal mechanisms. (a) Rigidity values on the fault plane from the 3D model used for the SGT database. The fault plane is from the focal mechanism derived in 3D model (green focal mechanism plot in Fig. 7). (b) Model 3D-3D: the same slip distribution as in Figure 8, obtained using the 3D model in (a) in the inversion and the focal mechanism derived from the same 3D model. (c) 1D rigidity values on the same fault plane as in (a). (d) Model 3D-1D: slip distribution obtained using the 1D model in (c) in the inversion and the same focal mechanism as in (a). (e) 1D rigidity values on the fault plane in the gCAP solution using the same 1D model (yellow focal mechanism plot in Fig. 7). (f) Model 1D-1D: slip distribution obtained using the 1D model in (e) in the inversion and the 1D gCAP focal mechanism. Red stars indicate the hypocenter location, and contours are rupture times. Surface topography is ignored in all 1D model calculations.
version algorithm. The SGT database can be established for seismic stations using complex 3D structure with realistic surface topography, which enables the calculations of accurate 3D synthetics in seconds on a single desktop or laptop PC without the need for parallel high-performance computing. This efficiency in calculating synthetics makes it practical to conduct slip-distribution inversions for finite-earthquake sources in 3D structures.

The capability for slip-distribution inversion in 3D structure is essential for studying the finite-source processes of moderate and large earthquakes \((M_w > 6)\) using waveforms within \(~150\) km away from the rupture areas. We demonstrated the importance of accounting for 3D structure and surface topography from synthetic tests and a practical case study for the \(M_w 6.4\) Ruisui earthquake in southeastern Taiwan. Our results for the Ruisui earthquake suggest that lateral heterogeneities in structure and surface topography can have notable influence on the slip-distribution inversions. Performing slip-distribution inversions by an efficient algorithm based on the SGT database approach opens up the possibility of developing automatic systems for near-real-time inversions of finite-source processes of earthquakes and the subsequent rapid predictions of earthquake-induced strong ground motions using state-of-the-art 3D velocity structures. This will greatly enhance the capabilities of current earthquake early-warning systems and make important contributions to seismic-hazard mitigation.

**DATA AND RESOURCES**

Seismic data used in this study include broadband records obtained from the Broadband Array in Taiwan for Seismology (BATS; [http://bats.earth.sinica.edu.tw](http://bats.earth.sinica.edu.tw), last accessed March 2016) and strong-motion records from the Central Weather Bureau (CWB) of Taiwan. For the 2013 Ruisui, Taiwan, earthquake, we used moment tensor solutions from several sources, including the Global Centroid Moment Tensor (GlobalCMT) Project ([http://www.globalcmt.org](http://www.globalcmt.org), last accessed March 2016), the generalized Cut-And-Paste solution ([http://tecdc.earth.sinica.edu.tw/gcap](http://tecdc.earth.sinica.edu.tw/gcap), last accessed March 2016), and the BATS catalog. This work has been supported by the Ministry of Science and Technology of Taiwan under Grant MOST104-2116-M-001-019 (M.-C. H and L. Z.). All figures except Figure 1 have...
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