Originally published as:

Diao, F., Wang, R., Aochi, H., Walter, T. R., Zhang, Y., Zheng, Y., Xiong, X. (2016): Rapid kinematic finite-fault inversion for Mw7+ scenario earthquake in the Marmara Sea: an uncertainty study. - *Geophysical Journal International*, 204, 2, pp. 813–824.

DOI: <http://doi.org/10.1093/gji/ggv459>

Rapid kinematic finite-fault inversion for an M_w 7+ scenario earthquake in the Marmara Sea: an uncertainty study

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Accepted 2015 October 19. Received 2015 October 19; in original form 2015 April 28

SUMMARY

During the 20th century, a series of devastating earthquakes occurred along the North Anatolian Fault. These generally propagated westwards, such that the main fault segment beneath the Marmara Sea appears as a seismic gap. For the nearby megacity Istanbul, rapid seismic hazard assessment is currently of great importance. A key issue is how a strong earthquake in the Marmara Sea can be characterized reliably and rapidly using the seismic network currently operating in this region. In order to investigate this issue, several scenario earthquakes on the main Marmara fault are simulated through dynamic modelling based on a 3-D structure model. The synthetic datasets are then used to reconstruct the source processes of the causal events with a recently developed iterative deconvolution and stacking method based on simplified 1-D Earth structure models. The results indicate that, by using certain *a priori* information about the fault geometry and focal mechanism, the tempo-spatial slip patterns of the input scenarios can be well resolved. If reasonable uncertainties are considered for the *a priori* information, the key source parameters, such as moment magnitude, fault size and slip centroid, can still be estimated reliably, while the detailed tempo-spatial rupture pattern may reveal significant variations. To reduce the effect induced by employing the inaccurate event location and focal mechanism, a new approach for absolute source imaging is proposed and tested. We also investigate the performance of the new source imaging tool for near real-time source inversion under the current network configuration in the Marmara Sea region. The results obtained are meaningful particularly for developing the rapid earthquake response system for the megacity Istanbul.

Key words: Instability analysis; Inverse theory; Earthquake source observations; Early warning.

1 INTRODUCTION

The kinematic rupture process is essential in describing a moderate to large-scale size earthquake, from which many fundamental characters such as slip distribution, seismic moment and rupture velocity can be obtained (e.g. Ji *et al.* 2002; Yagi *et al.* 2004). The rupture models which were obtained by inverting the seismogeodetic data for many strong earthquakes have highly improved our understanding of the physics of earthquakes (Heaton 1990) and played an important role in seismic hazard assessment (Dreger & Kaverina 2000; Babeyko *et al.* 2010). On the other hand, however, we often see large discrepancies between various rupture models of the same earthquake released by different research groups (e.g. Beresnev 2003; Mai *et al.* 2007). These discrepancies are usually caused not only by different data selections but also by different inversion methods used. The main problem behind this issue is that

the inversion problem is inherently ill-posed and some of the *a priori* information, such as the earth structure model and the fault geometry, are subjected to uncertainties (Beresnev 2003). Thus, a quantitative analysis of the uncertainties of the derived rupture models is most crucial.

A direct evaluation of the uncertainty of a kinematic rupture model is challenging as the true source model is unknown for a natural earthquake. Therefore, it is usually realized by synthetic tests, in which the data are generated from dynamic or kinematic rupture modelling. The reliability of the inversion results can then be evaluated by comparing the retrieved with the input parameters of the causal scenario event (Shao & Ji 2012; Konca *et al.* 2013; Razafindrakoto & Mai 2014; Zhang *et al.* 2015). So far, most of such synthetic tests focus on the influences of the data coverage and the model parametrization by assuming the hypocentre location, the fault geometry and the earth structure as the known parameters. In

Figure 1. Seismic stations (black triangles) currently operating in the Marmara Sea region. Grey lines show the simplified seismogenic faults given by Armijo *et al.* (2005). The dashed black line and black star show the fault trace and hypocentre of the dynamic rupture scenario used in this study.

practice, however, none of these presumed parameters can be obtained accurately and the errors in these parameters may highly affect the inversion results, too. Therefore, to evaluate the uncertainty of the rupture models more realistically, errors in the hypocentre location, the fault geometry and the earth structure should not be ignored.

In this paper, we focus on the Marmara Sea region that locates at the western end of the North Anatolian Fault (Fig. 1), which has experienced a series of devastating earthquakes during the 20th century. As no large earthquake occurred on the main fault segment in the Marmara Sea since its last rupture in 1776 (Pondard *et al.* 2007), this region is regarded as an important seismic gap and has a large potential for nucleation of next strong earthquakes (e.g. Hubert-Ferrari *et al.* 2000; Parsons *et al.* 2000; Hergert & Heidbach 2010; Ergintav *et al.* 2014). For the nearby megacity Istanbul, rapid seismic hazard assessment is currently of great importance. Possible rupture scales of the main Marmara fault beneath the Marmara Sea as well as the associated ground motion intensities have been investigated based on dynamic simulations (e.g. Oglesby & Mai 2012; Aochi & Ulrich 2015). The target of this study is to answer the question how reliably and rapidly we can characterize such large-scale earthquakes in the Marmara Sea using the regional seismic network.

The seismic network currently operating in the Marmara Sea region consists of 30 stations equipped with both broad-band and strong-motion sensors (Karabulut *et al.* 2011), most of which are distributed at the northern side of the fault (Fig. 1). We first simulate the scenario earthquakes through dynamic modelling based on a 3-D structure model and then use the produced synthetic dataset to reconstruct the source process of the causal events with a recently developed kinematic inversion scheme (Zhang *et al.* 2014) based on a simplified 1-D Earth structure. Particularly, we consider reasonable errors associated with the hypocentre location, the fault geometry and the earth structure and evaluate their influences on the inversion results. In addition, we test the performance of the real-time source inversion under the Marmara Sea network configuration.

2 METHOD

2.1 Synthetic data from dynamic scenario modelling

From the physical point of view, dynamic rupture simulations are more plausible compared with the kinematic rupture simulations. Therefore, the synthetic test using dynamic rupture scenarios is perhaps a more rigorous way for evaluating the uncertainty of kinematic source inversions (Konca *et al.* 2013; Zhang *et al.* 2015). For assessing the earthquake hazard along the North Anatolian Fault under the Marmara Sea, Aochi & Ulrich (2015) simulated a series of dynamic rupture scenarios supposing different pre-seismic stress distributions and hypocentre locations. In these simulations, the rupture propagation on the potential fault planes obeys the Mohr–Coulomb criterion and slip-weakening law through a 3-D boundary integral equation method (Aochi *et al.* 2000, 2011). The results show that the earthquake of a magnitude larger than 7 is likely to take place along the main Marmara segment of the North Anatolian Fault under the given situation. After the scenarios have been generated, a finite difference method (Aochi & Madariaga 2003; Aochi & Ulrich 2015) is used to calculate the complete synthetic seismograms at the regional scale (200 km × 120 km × 40 km), taking into account of 3-D heterogeneous structure (Bayrakci *et al.* 2013).

A representative rupture scenario (SE_1) from the dynamic simulations is shown in Fig 2(a). The synthetic seismograms for the given seismic network are extracted from the finite-difference output. The cut-off frequency of the synthetic seismograms is estimated from the minimum wave velocity in the elastic medium ($V_{\min} = 1500 \text{ m s}^{-1}$) and the numerical grid size ($\Delta s = 200 \text{ m}$) used: $f_{\max} = \frac{V_{\min}}{5\Delta s} = 1.5 \text{ Hz}$, which is sufficient for the purpose of our kinematic inversion. The three components of velocity seismograms are finally prepared with a sampling interval of 0.01 s (down sampled to 0.25 s in this study) for a time window of 120 s for all the stations, and this satisfies the stability condition of the forth-order finite-difference scheme, $\Delta t \leq 0.5 \frac{\Delta s}{V_{\max}}$, where $V_{\max}$ is the maximum wave velocity involved in the model ($V_{\max} = 8.0 \text{ km s}^{-1}$ here).

Figure 2. Comparison of the input and reconstructed slip models for the scenario earthquake SE_1. (a) is the input slip model with patch size of $0.4 \text{ km} \times 0.4 \text{ km}$. (b) same as (a), but downsampled to patch size of $4 \text{ km} \times 4 \text{ km}$. (c) and (d) are the reconstructed slip models by using the 1-D earth structure LM_1 and LM_2 (Fig. S1), respectively.

2.2 Inversion method

Both linear and nonlinear network methods have been widely used for the kinematic rupture inversion (Olson & Apsel 1982; Hartzell & Liu 1995; Ji *et al.* 2002; Sekiguchi & Iwata 2002; Yagi *et al.* 2004), and similar results could be obtained if the same model parameters and the same inversion norm are used in the two methods (Hartzell *et al.* 2007). In the linear method, the fault slip is discretized in both temporal and spatial domains, generally resulting in a large number of unknowns in case of large earthquakes. To obtain stable and physically reasonable solutions, various empirical constraints, such as smoothing the slip pattern, restricting the slip direction and minimizing the moment magnitude, are required. In comparison, the nonlinear method works with a pre-defined form of the local source time function, so that the number of unknowns can be reduced to three for each subfault, that is, the rupture time, the rupture duration (also called the rise time) and the final slip. The former two unknowns need to be estimated non-linearly. In general, the empirical constraints are also necessary for the nonlinear method. A well-known problem is the lack of an objective criterion for weighting these constraints relatively to the data misfit.

To reduce user's subjective influence on the inversion results, Zhang *et al.* (2014) proposed a new kinematic inversion scheme, called the iterative deconvolution and stacking (IDS) method. In this IDS method, synthetic Green's function deconvolution is applied to the waveform data to obtain apparent local source time functions from different stations. By stacking these apparent source time functions, one can then estimate the form and the initial time of the true sub-fault source time functions, remaining only its amplitude to be scaled through the least-squares fitting. In most cases,

the deconvolution and stacking procedure needs to be applied iteratively to resolve a complex multiple rupture process. In fact, the IDS method benefits from the complementary advantages between the traditional least-squares inversion and the array back-projection techniques. In particular, because it is largely free of empirical constraints such as the rupture velocity, the rise time and the shape of sub-fault source time functions, user's subjective influence on the inversion results can be minimized.

In the following section, we demonstrate the results of the IDS method applied to our synthetic data. In all tests, except for the hypocentre location and the focal mechanism as the known parameters, no constraint on the rupture propagation and duration is used. Note that the use of the hypocentre is aiming to a relative location of the slip distribution, that is it is assumed that the rupture initiates at the hypocentre and propagates with a finite velocity (normally smaller than the S -wave velocity). For an absolute location, the hypocentre is not necessarily to be known when using the IDS method, in which no assumption is made on the rupture initiation and propagation, that is each subfault can rupture at any time and in any form.

3 TEST RESULTS

3.1 Model design and test strategy

To quantify uncertainties in the earthquake source imaging based on the Marmara seismic network, four inversion tests are performed on synthetic data generated from the dynamic simulation, in which a realistic 3-D crust structure and a curved main Marmara fault segment are used.

Test A is to investigate the 3-D effect on the kinematic rupture model. In this test, the hypocentre location, the fault geometry and the focal mechanism are given as *a priori* information and exactly the same as used for generating the synthetic data. Green's functions used for the inversion are calculated based on 1-D structure models (Fig. S1). In addition, it is assumed that the rupture initiates at the given hypocentre and propagates with a velocity no larger than local P -wave velocity.

Test B is similar to Test A using the same data and the Green's functions for Model LM_1, but considering uncertainties in the hypocentre location and focal mechanism. The purpose is to evaluate the robustness of the kinematic inversion with respect to the *a priori* information, statistically.

Test C is designed for the purpose of rapid response. In this case, the hypocentre location has normally a large error and the focal solution is not yet available. The only reliable information is that an earthquake exceeding a certain threshold magnitude has happened in the target region. For the Marmara Sea region, we may assume that an earthquake of magnitude 7 and larger can only occur on the known fault segments, each with the roughly known mechanism. Therefore, in Test C we still use the same data and the structure model LM_1 for the inversion as used in the previous tests, but consider all known fault segments under the Marmara Sea, each of which has the potential to generate such a large earthquake. The inversion with the IDS method works then with the strategy of absolute location, that is, in contrast to Tests A and B, no assumption is made on the rupture initiation and propagation, that is each subfault can rupture at any time and in any form.

Finally, Test D is aimed to simulate a near real-time source inversion, in which the inversion scheme and all parameter settings used in Test C are adopted, but only the data are used which become

available in the moment of the inversion. Through such real-time inversion, the rupture model can be updated in a time interval as short as necessary.

3.2 Test A for the 3-D structure effect

Synthetic Green's functions based on a simplified 1-D structure model are usually used for seismic waveform inversions. In few cases, empirical Green's functions, if available, are useful, which are obtained by observations of small-scale earthquakes in the same source area and with similar focal mechanism as the target large-scale earthquake. Synthetic Green's functions based on 3-D structure models are rarely used, not just because they are numerically inefficient, but also because the 3-D structure with enough spatial resolution is usually not available. The present test is to evaluate the influences on the kinematic inversion by neglecting the 3-D structure effect. Two 1-D crust models are employed for calculating Green's functions: One is sampled from the 3-D structure in the source area, which has been actually used for generating the synthetic data (LM_1, Fig. S1). The other 1-D crust model is adopted from Karabulut *et al.* (2011) (LM_2, Fig. S1). The two 1-D crust models show clear differences particularly at shallow depths. For each of the two 1-D models, a Green's function database is prepared using the code QSEIS based on the orthonormalized propagator method (Wang 1999). Fig. S2 shows Green's functions based the 1-D model LM_1 (calculated with QSEIS), compared with those based on the 3-D model (calculated with the finite-difference method).

In previous studies, either the filtered velocity or displacement seismograms are referred to as the waveform data (e.g. Ji *et al.* 2002). Here, we first filter the original synthetic data in form of velocity seismograms with a 3rd-order Butterworth high-pass filter of 0.02 Hz to remove the influence caused by the low-frequency numerical drift in the data, and then with a causal low-pass filter corresponding to Brune's near-field velocity spectrum,

$$L(f) = \frac{1}{(1 + if/f_c)^2}, \quad (1)$$

where f_c is called the corner frequency. Thus, our waveform data trend to the velocity seismograms only for $f \ll f_c$. They become proportional to the displacement seismograms for $f \sim f_c$ and to the integral of displacement seismograms for $f \gg f_c$. The advantage of using the low-pass filter defined by eq. (1) is that no sharp high-frequency cut-off is necessary. In the present test, we choose $f_c = 0.05$ Hz. Theoretically a larger f_c value may increase the source resolution. In practice, however, we need to choose f_c sufficiently low, so that the artefacts caused by the 3-D effect become negligible. In the present case, substantial changes of the inversion results were observed for $f_c > 0.10$ Hz. However, the corner frequency can be increased to 0.20 Hz if additional static displacement data are available for a joint inversion (Fig. S3).

In the inversions based on the two 1-D models, the fault plane is discretized to a number of sub-faults of 4 km × 4 km size, each being treated as a point source. We compare the slip model obtained from inversion of the synthetic data with the original input one for their spatial pattern using the spatial cross-correlation coefficient,

$$C(P, I) = \frac{\sum_{j=1}^m P_j I_j}{\left[\sum_{j=1}^m P_j^2 \sum_{j=1}^m I_j^2 \right]^{1/2}}, \quad (2)$$

where m is the number of sub-faults, P_j and I_j represent the predicted and input slips on subfault j , respectively.

Figure 3. Comparison of the input and reconstructed source time functions of the scenario earthquake SE_1.

The source models obtained based on the crust structure models LM_1 and LM_2 are referred to as Slip_LM_1 and Slip_LM_2, respectively. As shown in Fig. 2, both slip models can well capture the input slip pattern and magnitude as well, with almost the same spatial correlation coefficients of 0.93 and 0.95, respectively. The total seismic moment (or moment magnitude) and the source time function are well retrieved, too (Fig. 3). As an example, a comparison between the original and inverted STF for the sub-fault with the maximum final slip is shown in Fig. S4. It reveals that the peak slip rate is clearly underestimated because of use of low-frequency data, but the rupture duration and final slip (total seismic moment) are well reconstructed.

The two predicted slip models differ only in the peak slip values and small-scale slip patterns, indicating the robustness of the kinematic inversion when the *a priori* information used is highly reliable. Data misfits are mostly dominated by high-frequency noises that are caused mainly by the 3-D wave propagation effect (Fig. 4).

Note that the network we selected in the present test includes both strong-motion and broadband stations, which are running currently. It raises the question how the station coverage influences the inversion results. In particular, it should be considered that records of the local and many regional broad-band seismometers may be clipped and therefore cannot be used in the case of strong earthquakes. In the supplementary material of this paper, we show that the inversion results remain robust even if only the strong-motion stations are used (see Fig. S5).

3.3 Test B for the effect of inaccurate *a priori* information

In previous studies, most synthetic tests for the kinematic inversion like checkerboard tests, are aimed to investigate the spatial resolution of sources on a known fault using the given observation network. Errors in the *a priori* information including particularly the fault location and geometry are rarely taken into account. In this section, the kinematic inversions are carried out using the same data as used in Section 3.2, but Gaussian noises are considered for the hypocentre location and focal mechanism (Table 1). Moreover, the original curved fault is simplified to a plane fault, located and oriented according to the hypocentre and focal mechanism (strike, dip and rake) to be tested. Thus, the geometric form of the fault is disturbed, too.

Figure 4. Comparison of the input (black) and predicted three-component velocity waveforms (red) for the scenario earthquake SE_1 based on the structure model LM_1.

Table 1. Standard deviation of the stochastically noised source parameters for the scenario earthquake SE_1 used in Test B.

Parameter	Hypocentre location (km)			Strike (°)	Dip (°)	Rake (°)
	North	East	Depth			
Standard deviation	3	3	3	5	5	5

Using the Monte Carlo approach, we generate totally 500 Gaussian distributed sets of *a priori* parameters with standard deviations shown in Table 1. The uncertainties of the hypocentre location and focal mechanism are based on the statistical results from the Marmara network and other regional seismic networks around the world (Karabulut *et al.* 2011; Wyss *et al.* 2011). Then the synthetic data are inverted using each set of the *a priori* parameters, but all based on the same structure model (LM_1).

To illustrate the inversion results, 20 examples are randomly selected from the 500 predicted source models (Fig. 5). Significant deviations of these selected source models from the input one can be seen in terms of the final slip pattern and magnitude. In Table 2, uncertainties of characteristic source parameters (moment magnitude, effective rupture length, mean fault slip, centroid location and peak slip) are evaluated based on the 500 test inversions. For

estimating the effective rupture length and the mean fault slip, only those subfaults are taken into account, which have slips larger than 20 per cent of the peak slip (Fig. 2a). This treatment is to remove the edge effect induced by spatial smoothing (Konca *et al.* 2013). For simplicity, the effective rupture length is equal to the effective rupture area divided by a fixed rupture width of 15 km. The histograms of the characteristic source parameters from the 500 inversions are shown in Fig. 6, where the estimated most probable value (MPV) and the true value of each parameter are marked by red and black lines, respectively. From the comparisons shown in Fig. 6 and Table 2, all MPVs of the source parameters differ from their true values by less than 20 per cent. Fig. 7 shows comparisons between the predicted and input source time functions (STFs) of the scenario earthquake. The 500 predicted STFs exhibit a systematic deviation in the middle of the rupture process, which is probably caused

Figure 5. Twenty randomly selected examples from 500 slip models for the scenario earthquake SE_1 derived based on disturbed *a priori* source parameters (Table 1), in comparison with the original input slip model (the top of each row).

Table 2. Comparison of the input and inverted source models for the scenario earthquake SE_1 from Test B. The inverted parameters are given by their median and standard deviation from the 500 inversions.

Parameter	M_w	Rupture length (km)	Mean slip (m)	Peak slip (m)	Lon (°)	Centroid location Lat (°)	Depth (km)
Input	7.19	69.33	2.04	4.62	28.57	40.87	8.93
Inverted	7.19 ± 0.03	62.6 ± 9.6	2.06 ± 0.15	5.61 ± 0.90	28.51 ± 0.05	40.87 ± 0.02	10.09 ± 0.76

Figure 6. Histograms of key source parameters of the scenario earthquake SE_1 based on inversion results using 500 disturbed *a priori* information sets (Table 1). The black lines represent the true value of the input model, while the red lines are the most probable value for each of the key parameters.

Figure 7. Comparison of source time functions of input model (black line) and inverted models (grey line) of the scenario earthquake SE_1 based on 500 set of disturbed source parameters.

by the simplified structure model LM_1 (compared with Fig. S1). Nevertheless, the single-event characteristic and the whole rupture duration are well estimated.

3.4 Test C for uncertainties by using the predetermined fault system

As already mentioned, this test is aimed at future applications of the kinematic inversion to early warning and rapid response systems. In current practice, timely information for event location and focal mechanism from automatic seismic data processing systems like, for example SeisComp3 (Hanka *et al.* 2000) still include large uncertainties. In case of large-scale earthquakes, initial automatic

solutions need normally to be manually revised. Therefore, we generally cannot rely on such automatic information when doing a rapid kinematic inversion. However, many automatic systems are currently able to detect large-scale earthquakes (e.g. $M_w \geq 7$) in their target region rapidly and with a relatively high reliability. In the present test, we assume that such events must have occurred on any segment of the known fault system. Under this assumption, we may use the absolute location strategy implemented in the IDS method, which works without the information of the hypocentre location, and start the inversion based on the whole fault system in the target region from a pre-prepared database.

It is not surprising that almost all large earthquakes ($M_w \geq 7$) in the Marmara Sea region are located on the identified seismogenic faults (Pondard *et al.* 2007). For this reason, all the major seismogenic faults (Fig. 1), which were identified by Armijo *et al.* (2005), are used in our inversion as the potential fault to generate the large-scale scenario event. For simplicity, the right-lateral strike-slip mechanism is assigned uniformly according to various geological and geomechanical investigations (Le Pichon *et al.* 2003; Armijo *et al.* 2005; Hergert *et al.* 2011). These faults are then divided into 4 km $\times$ 4 km subfaults. Each subfault is allowed to rupture at any time in any way after the origin of the event.

The results from Test C are shown in Fig. 8. The input earthquake finite-fault source is clearly retrieved in its location, size and magnitude, though there are some stochastic noises on neighbouring noncausal faults. Additionally, it is interesting to see that stable slip models can also be obtained if using only one-side stations (Figs 8c and d). Such results are meaningful for seismic monitoring networks in many subduction zones.

3.5 Test D for near real-time kinematic inversions

For purposes of tsunami early warning and earthquake rapid response, timely finite-fault source inversions are of great

Figure 8. Comparison of inverted kinematic source models of the scenario earthquake SE_1 with the input source rupture model. Panel (a) is the input model. Panel (b) is the source model obtained by inverting the data from all stations shown in Fig. 1. Panels (c) and (d) are the source models obtained by inverting only the data from stations located in the north and south sides of the main Marmara fault, respectively. The moment magnitudes outside the brackets account for the seismic moment distributed on the whole fault system, while that in the brackets correspond to the seismic moment on the main fault only.

importance (Babeyko *et al.* 2010). In Tests A–C, we have focused on the spatial resolution and stability of the source models. Here we address the question how fast such source models can be obtained theoretically for the Marmara Sea region. For this purpose, we adopt the inversion scheme and all parameter settings used in Test C but for a real-time data processing. Here the term ‘real-time’ means using only the data which become available during the inversion.

In the present case, we repeat the inversion each 10 s. The results are the real-time estimate of magnitude and slip distribution, which is shown in Figs 9 and 10. From the real-time magnitude curve, the final moment magnitude ($M_w = 7.19$) of the scenario earthquake seems to be available at about 30 s after the true event occurrence (Fig. 9). However, it is partly contributed by the numerical noises on neighbouring non-causal faults. Fig. 10 shows the slip distribution on the causal fault stabilizes not earlier than 50 s after the event occurrence, but the causal fault can be recognized already from

20–30 s. Note that the rupture duration of the earthquake is 20 s. Thus, the actual time delay for getting the final source model is at least 30 s, a large part of which is caused by the S wave travel times from the source to the stations.

3.6 Tests for different scenarios

In the supplementary material we show the test results on several different scenario earthquakes. The test scenario SE_2 aims at testing the performance of the kinematic inversion for events with smaller magnitude ($<M_w 7.0$) and fault size. Fig. S6 shows the inversion results obtained by applying Test A to the scenario earthquake SE_2. It reveals that the magnitude can be estimated correctly (± 0.1), but the fault size is underestimated slightly.

In Scenario SE_3, we adopt the rupture process derived from the 1999 Izmit earthquake (Çakir *et al.* 2003), but shift it to the main Marmara fault (Fig. S7). Scenario SE_4 represents a checkerboard

Figure 9. Moment magnitude curves for the scenario earthquake SE_1 obtained by the retrospective (red) and real-time reconstruction (blue) in comparison with the input one (black).

test with bi-lateral rupture (Fig. S8). From these two scenario tests we can make similar conclusions as obtained for Scenario SE_1.

In Scenario SE_5, we select a south fault branch in the Marmara Sea to investigate the robustness of the absolute location strategy (Test C and D). The input source model is the same as that of SE_1, but for simplicity the synthetic data are generated based on the 1-D structure model (LM_1). As shown in Fig. S9, the slip pattern, the rupture scale and the moment magnitude are all well retrieved, though the network coverage on the south side of the Marmara Sea is relatively poorer than that on the north side. However, the time delay for the rupture imaging and magnitude estimation becomes slightly larger than shown in Figs 9 and 10 because of a larger average distance between the source and stations.

4 DISCUSSION AND CONCLUSIONS

Recently the uncertainty issue in the kinematic source inversion has been widely recognized and discussed in the review paper by Beresnev (2003). Many previous authors have addressed the methodological differences (e.g. Hartzell *et al.* 2007; Razafindrakoto & Mai 2014), the structure effects (e.g. Graves & Wald 2001; Liu & Archuleta 2004; Konca *et al.* 2013), and the effects of data coverage and quality (e.g. Shao & Ji 2012; Zhang *et al.* 2015). Here we address the question how fast and reliable we can obtain a kinematic source model theoretically using the current seismic network configuration in the Marmara region. To reduce the influence of the uncertain *a priori* information on the kinematic inversion, we propose an absolute source location strategy and incorporate it in the IDS method. We also consider the effect induced by using the simplified structure model and discuss the performance of the real-time kinematic inversion for the Marmara region.

4.1 The IDS inversion method

The inversion method used in this study is the newly developed IDS approach (Zhang *et al.* 2014), in which the subfault source time functions are obtained based on a similar principle as used in the back-projection technique. With this technique, the IDS approach can be implemented so that various empirical constraints, such as limiting the variation range of the rupture start and duration, mini-

mizing the total seismic moment and optimizing the smoothness of slip distribution, which are generally used in the traditional waveform inversions, become unnecessary. So the particular advantage of the IDS method is that it works without any subjective influence. Moreover, the high computational efficiency of the IDS approach is useful for rapid source inversions. For the synthetic tests shown in this study, the CPU time needed is about 100 s on a single-processor desk PC for each inversion including the model setup and reading the data and Green's functions. Since the most time-consuming deconvolution and stacking procedures are independent among different subfaults, the code based on the IDS method can be easily parallelized. On a computer cluster with many hundreds of processors, for example, the computation time for the inversion may become negligible.

Differently to the standard non-linear kinematic inversion, the IDS method does not apply any empirical constraint on the rupture process, such as restricting rupture propagation, duration and rise time. In principle, a subfault is allowed to rupture at any time in any form. The advantage of this treatment is that the inversion algorithm can be easily automatized and any complicated rupture process can be considered. On the other hand, however, artefacts caused by the time-space trade-off may not be avoided. Consequently, local rupture velocity and slip-rate cannot be estimated robustly.

4.2 Effect of 3-D Earth structure

The structure effect is investigated in Test A, where the synthetic data from the 3-D dynamic modelling are inverted based on two simplified 1-D structure models (LM_1 and LM_2), respectively. Though LM_1 and LM_2 differ significantly in the shallow depth up to 5 km (Fig. 3), the corresponding inversion results are only slightly different if using the low-frequency data (filtering the data with the corner frequency of 0.05 Hz, see Section 3.2). In principle, it is expected that the use of high-frequency waveform information will improve the resolution of the kinematic slip model. In the present case, however, it seems that the structure effect becomes substantial for the corner frequencies larger than 0.10 Hz (Fig. S2). Moreover, we note that the increasing uncertainty with increasing corner frequency is not only caused by the structure effect, but also by the increasing trade-off between the spatial and temporal rupture distributions. In other words, even if exactly the same structure model were used for the data generation and inversion, we would generally observe the slip model becoming unstable if the corner frequency is chosen too large.

Though the uncertainty induced by using simplified earth structure was shown by Test A, one question raises: In what extent the input model can be recovered if precise Green's functions were used for the inversion. Such a test is shown in the supplementary material of this paper, where both the data generation and the inversion are based on the same 1-D earth structure model. As shown in Fig. S8, no substantial improvement has been observed by using the precise Green's functions, if the data are filtered by the low-pass filter as suggested. It is expected and also observed (not shown here) that use of the precise Green's functions allows inversions of high-frequency data and therefore enables a higher resolution of the source. However, this kind of tests is less meaningful for practical applications.

As shown in many previous studies (Konca *et al.* 2013), a joint inversion of the waveform and geodetic data is helpful to reduce the uncertainty of the slip model. For a quantitative evaluation in

Figure 10. Comparison between the input (top left) and real-time reconstructed slip models for the scenario earthquake SE_1. The moment magnitudes outside the brackets account for the seismic moment distributed on the whole fault system, while that in the brackets corresponds to seismic moment located on the main rupture fault.

the case of the Marmara Sea, we generate additionally the static displacements of all waveform data sites and use them in the joint inversion with the waveform data used in Test A (both datasets are equally weighted). Indeed, including the static displacement data improves the stability of the slip model, so that the corner frequency can be chosen as high as 0.20 Hz (Fig. S3).

4.3 Uncertainty of *a priori* information

In almost all of the previous waveform inversions, the hypocentre location and fault geometry are generally used as *a priori* information. Such approach is reasonable for teleseismic inversions. In such cases, the rupture signals are less sensitive to the focal mechanism and can only be located relatively to the hypocentre location. Otherwise, it should be ensured that the information of hypocentre and focal solution are available and reliable from independent and reliable methods. For purpose of rapid hazard assessment, however, it is necessary to assume large uncertainties in the *a priori* information being provided by automatic systems. Therefore, in this studies we have not only addressed the ‘normal’ uncertainties in the *a priori* source parameters (Test B), but also considered an extreme case for the Marmara Sea region, in

which no reliable information of hypocentre location and focal mechanism is available (Test C). It can be seen from Test B that, though the detail slip patterns are considerably affected by the uncertain *a priori* source parameters, the key source parameters (moment magnitude, fault size, slip maximum and centroid) are well estimated.

It is known that uncertainties of the first rapid hypocentre location are often so large that the earthquake can be easily assigned to a totally wrong fault segment. Moreover, a near real-time focal solution is even more challenging and normally not available so far. To overcome the problems associated with the poor *a priori* information of the target earthquake, in Test C we assume that an $M_w \geq 7$ earthquake cannot be generated randomly in space but only on an existing fault segment. Fortunately, there exists a good database of the fault system for the Marmara Sea region (e.g. Armijo *et al.* 2005). Thus we include all of its major fault segments having the potential to generate the scenario earthquake as the candidate fault in Test C. The inversion follows the principle of absolute rupture location without the use of the hypocentre. The satisfactory inversion results imply the sufficient resolution of the network on the one hand, and the robustness of the IDS method on the other hand.

4.4 Performance of real-time inversions

Test D is to evaluate the near real-time performance of the kinematic inversion under the Marmara network configuration. In practice, the kinematic inversion can be started as soon as the earthquake is detected to have exceeded a threshold magnitude. In Test D, the real-time inversion is started at 10 s after the earthquake occurrence under the same conditions as used in Test C and then updated each further 10 s. By comparing the results from the real-time inversion with those from the full waveform inversion (i.e. retrospective reconstruction), we can evaluate how fast the rupture process can be imaged by the monitoring network. Test D shows that the rupture process of the $M_w = 7.19$ scenario earthquake can be imaged with a time delay of about 10–15 s and its final magnitude and slip distribution can be obtained at about 60 s after the earthquake occurrence. Moreover, we find that the time delay for a reliable estimation of moment magnitude and slip pattern is not the same for rupture scenarios located at different fault branches (Fig. S9), but depends on the average distance between the source and stations. Though such real-time performance cannot serve the demand of the seismic early warning, the detailed and reliable earthquake source parameters provided in this way are still useful for purpose of tsunami early warning and rapid hazard assessment.

In summary, near real-time source characterization of large-scale earthquakes ($M_w \geq 7$) under the Marmara Sea is feasible. Providing the real-time data acquisition for the current network and a good database of the active fault system, all key source parameters that are relevant for purpose of the rapid hazard assessment can be estimated without substantial uncertainties. The theoretical time delay between what can be resolved and what has been really occurred on the earthquake source is in the order of 10–15 s. This time delay is caused mainly physically by the *S*-wave propagation from the source to the network. In practice, a larger time delay should be considered because of the time required additionally for data transmission and inversion. The latter can be generally reduced to a few seconds through parallelization of the inversion code, which can, in principle, be easily done using the IDS method.

ACKNOWLEDGEMENTS

This work was supported by the MARSite project founded by the European Union (Grant No. 308417), the National Natural Science Foundation of China (Grant No. 41304017), the Visiting Scholar Program of Chinese Academy of Science (Grant No. 2012–128) and the International Partnership Program for Creative Research Teams of the Chinese Academy of Sciences (CAS/SAFEA) (Grant No. KZZD-EW-TZ-05). We thank A. Ozgun Konca, an anonymous reviewer and the editor for their constructive comments.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this paper:

Figure S1. *P*-wave velocity and density of the two layered earth structure models used for the synthetic tests. LM_1 and LM_2 are adopted from Bayrakci *et al.* (2013) and Karabulut *et al.* (2011), respectively. The *S*-wave velocity is derived from the *P* wave velocity by assuming a uniform Poisson ratio of 0.25.

Figure S2. Comparison of synthetic seismograms (Green's functions) for a point source at the hypocentre of the scenario earthquake SE_1 (Fig. 1), calculated based on the 3-D and 1-D (LM_1) earth structure models, respectively. Panels (a), (b) and (c) show comparisons at different frequency bands.

Figure S3. Inversion results for the scenario earthquake SE_1 by using different corner frequencies of the low-pass filter. Panels (b)–(f) in the left column are results obtained by inverting the seismic waveform data only, while (b')–(f') on the right column are results from joint inversion of seismic waveform data and geodetic displacement data. White stars show the hypocentre of the scenario earthquake.

Figure S4. Comparison of the input and inverted sub-fault source time functions of the scenario earthquake SE_1 at the location with the maximum final slip. The solid black and red lines show the input and inverted moment rate (left *Y* axis), while the dashed black and red lines represent the corresponding cumulative moment (right *Y*-axis), respectively.

Figure S5. Comparison of the input slip model (a) and the inverted slip models for the scenario earthquake SE_1 using the strong-motion station only (b) and all stations (c), respectively. The station network is shown in Fig. 1.

Figure S6. Test results for the scenario earthquake SE_2 with a relatively smaller moment magnitude (M_w 6.9) and rupture scale than SE_1. Panels (a) and (b) are the input and inverted slip models, respectively, (c) the comparison of the input and output source time functions, and (d) the data fit.

Figure S7. Test results for the scenario earthquake SE_3. Panels (a) and (b) are the input and inverted slip distributions, respectively, (c) the comparison of the input and output source time functions of the earthquake, and (d) the data fit.

Figure S8. Synthetic checkerboard test (scenario earthquake SE_4). Panel (a) is the input slip model, (b) the inversion results, in which the same 1-D structure model (LM_1) is used for the data generation and inversion, (c) the inversion results, in which the data are generated using the 3-D structure model for the Marmara region, while the Green's functions for the inversion are calculated based on the simplified 1-D model (LM_1), and (d) the data fits for the test strategies (b) and (c), respectively.

Figure S9. Test results of the near real-time inversion for the scenario earthquake SE_5 located at the south Marmara fault branch. (a) Moment magnitude curves obtained by the retrospective (red) and real-time reconstruction (blue) in comparison with the input one (black). (b) Comparison between the input (top left) and real-time reconstructed slip models. The moment magnitudes outside the brackets account for the seismic moment distributed on the whole fault system, while that in the brackets correspond to seismic moment located on the main rupture fault only (<http://gji.oxfordjournals.org/lookup/suppl/doi:10.1093/gji/ggv459/-/DC1>).

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