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Numerical earthquake models of the 2013 Nantou, Taiwan, earthquake series: Characteristics of source rupture processes, strong ground motions and their tectonic implication

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ABSTRACT

On 27 March and 2 June 2013, two large earthquakes with magnitudes of M_L 6.2 and M_L 6.5, named the Nantou earthquake series, struck central Taiwan. These two events were located at depths of 15–20 km, which implied that the mid-crust of central Taiwan is an active seismogenic area even though the subsurface structures have not been well established. To determine the origins of the Nantou earthquake series, we investigated both the rupture processes and seismic wave propagations by employing inverse and forward numerical simulation techniques. Source inversion results indicated that one event ruptured from middle to shallow crust in the northwest direction, while the other ruptured towards the southwest. Simulations of 3-D wave propagation showed that the rupture characteristics of the two events result in distinct directivity effects with different amplified shaking patterns. From the results of numerical earthquake modeling, we deduced that the occurrence of the Nantou earthquake series may be related to stress release from the easternmost edge of a preexistent strong basement in central Taiwan.

1. Introduction

On the 27th of March 2013, a moderate-large earthquake (M_L 6.2) struck Nantou County in central Taiwan. About 2 months later, on the 2nd of June, a larger earthquake (M_L 6.5) again occurred at almost the same location. These two events were named the Nantou earthquake series in 2013 (also called the 0327 and 0602 events). Strong ground shakings were observed at Nantou County with a seismic intensity of 6 (250–400 gal), and many areas, including the densely-populated Taichung metropolitan, experienced a seismic intensity larger than 5 (80–250 gal). This earthquake series caused the collapse of three buildings, deaths of six people, and several injuries.

As shown in Fig. 1, the 2013 Nantou earthquake series occurred in a seismically active area, where several moderate to large earthquakes were recorded in the last century (also see Table 1). Between August 1916 and January 1917, three historical earthquakes (called the Nantou earthquake series in 1916–1917) occurred in this area with local magnitudes between M_L 6.2 and M_L 6.8. The location of a M_L 6.7 aftershock of the 1999 Chi-Chi earthquake in June 2000 (Kao and Chen, 2000; Chen et al., 2002; Chi and Dreger, 2004) was also in the vicinity of the 2013 Nantou earthquake series.

Both centroid moment tensors (CMT) of the two earthquakes provided by the Central Weather Bureau (CWB) show thrust faulting mechanisms with two north–south striking nodal planes, with one dipping toward the east with a shallower dipping angle, and the other dipping toward the west with a steeper fault plane (Fig. 1; also see Table 1). Several felt aftershocks had been recorded after the two events. The epicenters of the two aftershock sequences form two different alignment trends, one in the northwest–southeast direction and the other in the northeast–southwest direction. On the map (Fig. 1A), the patterns of aftershock distributions appear to be complementary in space even though the distance between the two mainshocks is less than 10 km. A cross section along c–c' is shown in Fig. 1B. These two events were located at depths of 15–20 km, which implied that the mid-crust of central Taiwan is an active seismogenic area even though there is no evidence show a subsurface structure directly related to any faults at surface.

A study of fault slip distributions of the Nantou earthquake series based on geodetic data proposed by Chuang et al. (2013) indicates that models with east-dipping fault planes can be most

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Table 1
Event list for moderate to large earthquakes in central Taiwan recorded in the last century.

	Date (yyyy/mm/dd)	Time[a] (hh:mi:ss)	Long. (°E)	Lat. (°N)	Depth (km)	Strike (°)	Dip (°)	Rake (°)	M_L
1	1916/08/28	15:27:00.0	121.00	24.00	45.0	–	–	–	6.8
1	1916/11/15	06:31:00.0	120.90	24.10	3.0	–	–	–	6.2
1	1917/01/05	00:55:00.0	121.00	24.00	–	–	–	–	6.2
1	1917/01/07	02:08:00.0	120.90	23.90	–	–	–	–	5.5
2	1999/09/21	01:47:15.9	120.82	23.85	8.0	3	30	66	7.3
2	2000/06/11	02:23:29.5	121.11	23.90	16.2	355	17	63	6.7
3	2013/03/27	10:03:19.6	121.05	23.90	19.4	355	25	75	6.2
3	2013/06/02	13:43:03.2	120.97	23.86	14.5	2	29	83	6.5

[1]Nantou earthquake series in 1916–1917 (taken from Central Weather Bureau historical earthquake catalog).
[2]1999 Chi-Chi earthquake mainshock and its biggest aftershock.
[3]Nantou earthquake series in 2013.
[a] Taiwan standard time (UT + 8).

likely compatible with the observations. The slips were concentrated at depths between 9 and 16 km, with primarily reverse, updip slip. Their results provide static slip patterns of the two events. In this study, we investigated the numerical earthquake models of the Nantou earthquake series, including their detailed rupture time history and the generation of strong ground motions. Joint source inversions by using teleseismic, near-field strong motion, and GPS coseismic data were first carried out. Unlike geodetic inversion, which can only provide the total slip pattern, the three data sets used in this joint inversion can constrain both the details of the rupture process (by waveform data) and the total slip pattern (by geodetic data). Then, using the source inversion results as the input rupture models, 3-D wave propagation simulations were performed for the Taiwan region. Using precise numerical earthquake models, the nucleation of this earthquake series, propagation of strong ground shaking, and mechanism of the seismogenic area in central Taiwan are discussed. The results of this study could also be applied to the worldwide areas where have similar case of basement boundary earthquakes as well as hazard assessment, such as the 1909 Lambasc (Provence, France) earthquake (Chardon and Bellier, 2003), the Kitayuri thrust system in northeast Honshu, Japan (Awata and Kakimi, 1985), and southern California (Shaw et al., 2015).

2. Source rupture models

2.1. Data

To understand the mechanisms of the Nantou earthquake serious, we investigated the rupture processes of these two events based on joint source inversion. Three data sets were used in the inversion, including teleseismic body wave, near field GPS coseismic displacement and ground motion data. The teleseismic data have good data quality and azimuthal coverage to the earthquake which provide a first-order determination of fault rupture behavior. The near-field GPS coseismic deformation data provide a good constraint on the total spatial slip pattern. In addition, the two events are well recorded by dense regional seismic networks, which can provide further constraints on the temporal rupture processes.

Eighteen and sixteen teleseismic stations were used for the 0327 and 0602 event, respectively. The stations provided good azimuthal coverage and were located between 30° and 90° to avoid the complex earth structure (distributions of the stations can be found in supplementary Figs. S1.1 and S2.1). These data were digital recordings obtained from IRIS (the Incorporated Research Institutions for Seismology). Signals were deconvolved from the instrument response, re-sampled to 10 points per second and a band-pass filter (0.01–0.5 Hz) was applied. We used a time window of 25–30 s after the *P* arrival time with an addition of 10 s before the *P* arrival. The GPS coseismic displacements used in this study were compiled by TEC GPS Lab (http://gps.earth.sinica.edu.tw). There were 316 sites of three-component GPS coseismic displacements. We selected displacements with standard deviation less than 10 mm in all three components to be used in the inversion. Near field seismic records were from Broadband Array in Taiwan for Seismology (BATS) and CWB real-time strong motion data (RTD). These two data sets provided a good azimuthal coverage around the source area. We considered velocity seismic records in the inversion, all the strong motion data were integrated from acceleration to velocity, and then band-pass filtered between 0.05 Hz and 0.2 Hz. In total, 32 records were selected for the 0327 event and 40 records were considered for the 0602 event. We used a waveform time-window of 35–50 s that starts from the event original time with a sampling rate of 0.1 s.

2.2. Method

The finite fault source inversion problem is usually formulated in a linear form, $\mathbf{Ax} = \mathbf{b}$ where $\mathbf{A}$ is the matrix of Green's functions, $\mathbf{b}$ is the observed data vector and $\mathbf{x}$ is the solution vector of slip characteristics on each subfault, including amplitude, direction and rupture time (Hartzell and Heaton, 1983). We applied the multiple-time windows technique in the inversion procedure that provides a more detailed slip spatial and temporal resolution. The program performance was improved by using a parallel Non-Negative Least-Squares (NNLS) inversion technique (Lee et al., 2006). A misfit function, defined as $(\mathbf{Ax}-\mathbf{b})^2/\mathbf{b}^2$, was used to evaluate the quality of a solution.

In matrix $\mathbf{A}$, the teleseismic Green's functions were calculated by using the approach developed by Kikuchi and Kanamori (1982), where the near source structure was given by using a 1-D Taiwan average crust model (Chen and Shin, 1998) while the receiver side structure used a global 1-D IASPEI91 model (Kennett and Engdahl, 1991). The teleseismic synthetic waveforms were filtered between 0.01 and 0.5 Hz. For the geodetic Green's functions, we used the analytic expressions of Okada (1992) to calculate the horizontal and vertical static displacements where surface deformation results from a uniform slip over each subfault. The 3-D synthetic Green's functions for near field ground motion station was generated by the spectral-element method (SEM, Komatitsch and Tromp, 1999; Komatitsch et al., 2004), with a tomography velocity model taken from Huang et al. (2014). The seismic synthetic waveforms were filtered between 0.05 and 0.2 Hz in the same frequency range as for observed data.

In the inversion, we used 28 time windows of 0.2 s length, each window overlapping 0.1 s, leading to each subfault the possibility to slip within 2.9 s after the rupture starts. A maximum rupture velocity, $Vr = 3.0$ km/s, was assumed to approximate the full