1999 Chi-Chi Earthquake: A Case Study on the Role of Thrust-Ramp Structures for Generating Earthquakes

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Abstract The 21 September 1999 Chi-Chi earthquake ($M_w$ 7.6) occurred on east-dipping shallow thrust faults that produced a high-relief surface rupture. Extraordinary surface breaks appeared that could be clearly traced for about 100 km across many counties. These thrust faults, the Chelungpu and Shihkang, are part of an active fold-and-thrust belt related to ongoing recent arc-continent collision. Measurement of slip vectors along the earthquake rupture indicates that the orientation of the maximum shear stress changed from a westward direction (N70–90°/H11034 W) on the Chelungpu fault to a northwestward direction (N30–40°/H11034 W) on the Shihkang fault. The stress field underwent a clockwise rotation of about 40° during the Chi-Chi earthquake. Near-rupture vertical displacements in the hanging wall of the Shihkang fault have more cumulative displacement than on the Chelungpu fault, which is consistent with Global Positioning System (GPS) measurements. Maximum vertical offset on the rupture was found to be about 10 m by the surficial rupture and GPS measurements. In addition, analysis of crustal deformation by GPS measurements on the hanging wall defines a coseismic uplift related to a fault ramp structure.

Our synthesis of geological and geodetic analyses shows the importance of ramp structures associated with thrust faults for generating large earthquakes and provides a general framework for understanding earthquake in fold-and-thrust belts. Large surficial coseismic uplift and strong asperities appear to be a function of fault ramp geometry. Our analysis also indicates that, in general, ramp structures in fold-and-thrust belts may have a high potential in generating large earthquakes.

Introduction

The structural configuration of the Western Foothills of Taiwan consists of a series of east-dipping subparallel thrust faults and related folds (Suppe, 1981) (Fig. 1a). The 21 September, 1999 earthquake occurred on the Chelungpu and Shihkang faults. Coseismic displacement on the faults produced a spectacular well-exposed surface rupture. Previous well-developed coseismic earthquake ruptures are also documented with earthquakes of 1906 ($M$ 7.1) and 1935 ($M$ 7.1) in western Taiwan (Omori, 1907; Otuka, 1936).

Most of the folds in the Western Foothills of Taiwan have been interpreted as hanging-wall folds associated with displacement over ramp structures (Suppe, 1986). Ramps are relatively steep parts of faults and have been interpreted to be zones of locking and strain accumulation (Dolan et al., 1995). Ramp structures, therefore, have a high potential for producing large earthquakes (Shaw and Suppe, 1994). This article proposes that in order to characterize the measurements of coseismic rupture and GPS data associated with seismic results, it may be helpful to interpret the entire process as being related to the structural configuration of a fold-and-thrust belt.

In this study, we focus on the spatial variation of slip direction along the earthquake rupture. We identify the surface rupture deformation mechanisms and propose possible tectonic interpretations. Vertical and horizontal displacements and slip direction on the earthquake rupture were directly measured from slickensides within bedrock or disrupted man-made features such as city streets, embankments, bridges, riverbanks, fences, or dams where a fault plane could be defined in the field. However, disruptions within a thrust zone commonly destroy the reference points. Several good examples of ruptures exist across the linear man-made features that can measure the vertical and horizontal displacements and slip directions.

Chi-Chi Earthquake Ruptures

The Chi-Chi earthquake ($M_w$ 7.6) produced a visible surface rupture of 100 km in length in front of the Western
Foothills along the Shihkang and Chelungpu faults (Fig. 1). The surface rupture can be divided into four segments, the Chushan, Tsaotun, Shihkang, and Cholan segments, based on geologic characteristics (Fig. 2). The Chushan and Tsaotun segments are part of the Chelungpu fault, and the Shihkang segment is part of the Shihkang fault, where each segment is bounded by right-lateral strike-slip faults. The major rupture had a sinuous trace that followed the boundary between the Western Foothills and the Taichung piggyback basin. The irregularities have caused strike-slip faults that cut through the major thrust trace forming the protruding rupture traces. To study the rupture, we trenched across the Chelungpu fault. Results of trenching document at least three earthquake events on the Chelungpu fault. Supporting
Figure 2. The Chi-Chi earthquake causes a surface rupture in front of the Western Foothills, which is subdivided into the Chushan, Tsaotun, Shihkang, and Cholan segments. The slip vector and vertical displacement of rupture indicate: Chushan and Tsaotun segments along the Chelungpu fault: N70–90°W, 0.2–4 m; Shihkang segment along the Shihkang fault: N30–40°W, 3–8 m, Cholan segment: N35°W. The seismic reflection profile is reprojected onto the cross section AA' (Chiu, 1971; Suppe, 1986). CHF, Changhua fault; CLPF, Chelungpu fault; STF, Shuangtung fault; SYF, Sanyi fault; HLF, Houli fault; SKF, Shihkang fault.
evidence for previous earthquakes on the fault is the observation that the Chelungpu rupture followed pre-existing Holocene terrace scarps. In addition, six to eight stream terraces in the hanging wall of the Chelungpu fault are well exposed adjacent to the recent fault rupture (Chen et al., 2000). Uplifted stream terraces are often important indicators of active faults (Allen et al., 1984). Our new radiocarbon dates indicate that the three terraces on the hanging wall of the rupture formed at $300 \pm 70$ yr B.P., $800 \pm 30$ yr B.P., and $1200 \pm 200$ yr B.P. These geochronological data indicate that the Shihkang and Chelungpu faults had been active at least since the Late Quaternary.

The objectives of this research are to assess characteristics of the Chi-Chi earthquake rupture based on the recognition and measurement of displacement. The earthquake rupture extends along the two faults of the Chelungpu and Shihkang faults based on the geologic characteristics. Therefore, we focus on the contribution of each fault to the deformation pattern.

Chushan and Tsaotun Segments

The Chushan and Tsaotun segments extend along the eastern margin of an eastward-thickening wedge of Pliocene–Recent piggyback basin deposits. Pliocene strata on the hanging wall override Recent deposits and Holocene terraces in the footwall. Much of the near-surface deformation is expressed by reverse faulting, but in some cases surface folding was documented. Trenching across this folded area found tilted colluvial layers. Folding scarps show only minor shortening at the surface and less cumulative vertical displacement than segments of the rupture characterized by faulting. The near-rift surface expression of folded area is a broad warp, which has vertical displacements ranging from 0.2 to 4 m.

The horizontal slip direction on the Chushan and Tsaotun segments was oriented N70°–90°W indicating a pure thrusting related with the rupture (Fig. 2). On the hanging wall, except for the major rupture, several coseismic minor fractures of back thrusts and strike-slip faults are distributed. The major rupture is regularly offset by the northeastern-trending strike-slip fault. In addition, the southernmost Chushan segment is terminated by a northeastern-trending of right-lateral strike-slip fault with a slip vector oriented N50°E. This measured the northeastern-trending orientation that closely approximates a synthetic strike-slip fault with the structural expression of strain ellipse (Fig. 2).

Shihkang and Cholan Segments

Surface rupture along the Shihkang segment occurs within Pliocene shale and is interpreted as a bedding-slip fault. Coseismic movement proximal to the rupture shows northwest slip with horizontal displacements of 7–9 m and vertical displacement of 3–10 m based on field and GPS measurements (Figs. 2, 3a,b, 4) (Land Survey Bureau [LSB], 1999; Central Geological Survey [CGS], 1999). In the northernmost rupture of the Cholan segment, a broadly deformation zone is displayed with folding and faulting (Fig. 1b). An anticlinal fold (Fig. 5), about 1 km wide and 12 km long, contains a conspicuous backthrust on its east flank along a pre-existing fault. In addition, a folding scarp on its west flank may be associated with an east-dipping blind thrust under the anticline. This anticline is present as a pop-up structure characterized by minor features of tensile cracks, normal faults, and reverse faults (Lee et al., 2001). The earthquake-generated anticline associated with the Chi-Chi earthquake is located at the pre-existing Tungshih anticline (Fig. 1b). The broadly deformed region of the Cholan segment bounded by two northwest right-lateral strike-slip faults (Fig. 1b). Many northeast-trending tensile fractures are typically several hundreds of meters long and form an en echelon pattern along the strike-slip faults. These fractures also accommodate northwest extension, indicating that they were produced by dextral shear.

The Shihkang segment has a strike of N10°–20°E. Slip direction measurements along this segment are oriented N30°–40°W. The Cholan segment contains folds with maximum compressive strain axes oriented N35°W, similar to the Shihkang segment (Fig. 2). The measured slip vectors along the rupture are compatible with the actual vectors revealed by previous published GPS data (Yu et al., 1997) and new GPS measurements after the Chi-Chi earthquake (Fig. 3a,b). Measurement along the fault rupture indicates that the orientation of slip changes from a westward sense on the Chelungpu fault to a northwestward sense on the Shihkang fault (Fig. 2). Note that deformation associated with NE- to NE–E–striking reverse faults and folds within the Shihkang-Cholan segments are oblique to the Shihkang fault. The basic geometry of the faults and folds along the Cholan and Shihkang segments is consistent with wrench deformation (Fig. 2) (Wilcox et al., 1973; Harding, 1976), for example, the Tungshih anticline with a highly faulted core is based on structures predicted from wrench deformation. We interpret the Shihkang and Cholan segments as the result of left-lateral wrenching between two right-lateral strike-slip faults during the earthquake. The Shihkang fault is a major oblique-slip thrust that inherited the compressional component of wrench faulting consistent with the schematic geometry of strain ellipse (Fig. 2).

The Chi-Chi earthquake ruptures often inherit the pre-existing structures, such as fault and fault scarps. For example, a coseismic anticline in the Cholan segment is along the Tungshih anticline, and the pre-existing fault is reactivated by a west-dipping backthrust in its east limb. Along the master rupture of the Chelungpu and Shihkang faults, river terraces are only located on the hanging-wall forming a fault scarp about 3–15 m height. Holocene terraces have been tilted and warped, a characteristic that terrace scarps usually inherit along the traces of fault rupture and kink-fold hinge (Chen et al., 2000; Suppe, 2000). Based on the neogeomorphic analysis and detailed rupture mapping that provides...
an earthquake-generating structure for understanding neotectonic features, we infer that the frontal Western Foothills in central Taiwan is a very younger and active fold-and-thrust belt.

Global Positioning System

After the Chi-Chi earthquake, the LSB, Ministry of Interior Taiwan, was measured using the technique of GPS. The complete GPS coverage included 70 sites on the hanging wall and 180 sites on the footwall of the rupture that are related to a stable site on Kingmen Island, west of the Taiwan Strait (LSB, 1999). The GPS measurements obtained after the earthquake provide valuable geodetic data for understanding crustal deformation both near the rupture and over a large surrounding area. In the whole area, the vertical displacements are defined as a 5- to 30-km-wide zone on the upthrown block of the Western Foothills, which was coeval with far-rupture subsidence on the Central Range, east of the uplift zone. West of the Western Foothills, the Taichung...
The deformation recorded from the GPS observations show a slip vector oriented N30–40°W (Fig. 3b) and coseismic elevation changes of 3–10 m on the hanging wall of the Shihkang fault (Fig. 3a,b). The main slip vector for the Chelungpu fault is N60–70°W, with elevation changes of 0.5–4.0 m on the hanging wall. The footwall of these faults approximately shows southsouthwest slip of about S40–60°W. However, the Shihkang fault seems to have more cumulative vertical displacement than the Chelungpu fault. The GPS calculated vertical displacement is generally consistent with field measurements along the surficial rupture. The variations of vertical and horizontal displacement in the two faults probably imply the spatial and lithological heterogeneities of the fault zone in terms of the stratigraphic and structural characteristics.

The GPS measurements show that the near-surface slip direction has a clockwise rotation of about 30° from the southern to northern blocks. The surficial rupture measurements on the southern block were about N70–90°W, which is inconsistent with the GPS data on the hanging wall, about N60–70°W, but the northern block closely matches both measurements. Geodesy data, which are commonly averaged over long timescales of a few months or years, show near-surface deformation and represent long-term crustal deformation compared with during the earthquake. Although the basics of this procedure have been worked out, there still remain some problems with this type of presentation. The problem arises because earthquakes often occur as several subevents within the mainshock and aftershocks, which may have diverse slip vectors (Kao and Chen, 2000). The geodetic data, however, only represent the amount of vectors combined with the slip vectors during the mainshock. Seismic inversion and strong-motion observations indicate that the rupture propagated northward from the epicenter during the mainshock (Kikuchi et al., 1999; Huang et al., 2000, Lee and Ma, 2000). It seems to be divided to two major subevents identified from the reconstructed wavefield during the fault rupture. Rupture modeling infers that the earthquake rupture was initially concentrated in the south region and associated with westward thrusting along the Chelungpu fault. In the latter, the fault rupture propagated northward, with northwest left slip (Kikuchi et al., 1999). The northward-propagating mainshock produced northwestward thrusting along the Shihkang fault. Unfortunately, coseismic deformation can produce slip-direction changes that are too abrupt and too fast to be resolved by changes of slip utilizing geodetic measurements during the mainshock. Based on the integrated and identical slip direction from field measurements (C. T. Lee et al., 2000; Y. H. Lee et al., 2000), our interpretation of the data sets indicate that motion initially propagated westward on the Chelungpu fault. In the latter, subevent northwest-trending left slip probably activated the Shihkang fault, which simultaneously activated the southern block again. It produced the geodetic data as a WNW–trending slip vector.

Discussion

The seismologic model developed for the 21 September 1999 earthquake provides an approximated 20–30° east-dipping reverse-fault deformation pattern (Chang et al., 2000). More detailed information can be extracted by combining measurements of surficial rupture and GPS. Our data suggest that the deformation can be divided into two different structural domains related to regional deformation during the Chi-
The sense of slip measured along the rupture is consistent and left-lateral thrusting (N30–40°). Study (Lee and Ma, 2000; Iwata) occur along the Chelungpu fault based on the waveform characteristics. In the Chi-Chi ruptures appear to have several strong asperities on its fault at about 3–10 km depth. A large asperity has been defined along the Shihkang fault, and two small asperities occur along the Chelungpu fault based on the waveform study (Lee and Ma, 2000; Iwata et al., 2000). The characteristics in seismicity and lithological properties are too different along the Chelungpu and Shihkang faults and reveal that spatial heterogeneities of the fault plane may be induced to the nonuniform behavior of the fault plane.

Measurements of slip indicators along the rupture document pure thrusting (N70–90°W) on the Chelungpu fault and left-lateral thrusting (N30–40°W) on the Shihkang fault. The sense of slip measured along the rupture is consistent with GPS measurements (LSB, 1999) and distribution of slip of the focal solution of the mainshock (Kao and Chen, 2000). The orientation of the maximum shear stress in the Chelungpu and Shihkang faults is approximately similar to the focal solution of S1 and S2 subevents (Kao and Chen, 2000) and S3 and S4 subevents, respectively. Moreover, the inversion of regional broadband waveforms and strong-motion observations shows that the rupture propagated northward from the epicenter (Huang et al., 2000; Kao and Chen, 2000). The mainshock of the Chi-Chi earthquake, however, may be modeled as two major subevents. Apparently, coseismic rupturing initially activated the southern segments of the Chelungpu fault and later extended to the north of the Shihkang fault. Stress field has to be a clockwise rotation and equaled about 40° during the Chi-Chi earthquake.

Field mapping and cross sections indicate the Chelungpu fault has an east-dipping ramp structure at about 0–6 km depth (Suppe, 1986). Our data also suggest an east-dipping fault plane with a dip of 20–30° based on the measurements of the surficial rupture. In addition, our trenches across the thrust scarp also suggest a 20- to 30°-dipping fault plane. The fault-plane solution of the mainshock defines a fault plane dip of 20–30° and a centroid depth of 8–10 km (Chang et al., 2000). From the previous observations, the fault-plane angle determines the shape of a ramp structure, east-dipping about 20–30°. The ramp geometry of the thrust fault commonly results in broadly geometric heterogeneities along the fault system. Fault ramps have rather steep fault planes on the thrust system and as a result are zones of locking and strain accumulation. The strain accumulated area in the fault zone often formed an asperity, and large earthquake occurrence is associated with the strongest asperities on the fault (Ruff, 1992). Hence, reverse faults have frequently produced large earthquakes on ramp structures (Shaw and Suppe, 1994). In addition, fault ramps have fewer earthquakes forming aseismic zones that have higher large-earthquake potential than detachment (Namson and Davis, 1988).

The hanging wall of the Chelungpu fault was aseismic for several decades before the Chi-Chi earthquake (Fig. 6). Also numerous smaller earthquakes (M < 5) and aftershocks were documented east of the aseismic zone. The ramp structure of the Chelungpu fault is inferred to be beneath this aseismic area, based on these observations.

In addition, the configuration of the ramp may be inferred by changes in coseismic elevation and/or geodetic data. The occurrence of discrete belts of uplift and subsidence in the hanging wall is possibly a superficial phenomenon that may be related to thin-skinned tectonics involving a succession of active ramps and detachments. Vertical deformation of the thrust sheet is controlled by the slope of the fault (Jackson and Biham, 1994). The thrust sheet associated with the rupture must bend upward as it is translated up a ramp, causing near-surface uplift. Therefore, displacement along a ramp should produce a large vertical displacement field relative to detachment. The uplifted field measured from GPS data should be a proxy for the position of the subsurface ramp structure. Similar findings have been documented in the Himalaya’s (Jackson and Biham, 1994) and the Alps (Jouanne et al., 1995). Therefore, the dimensions of the uplifted area along the Chelungpu and Shihkang faults, as indicated by vertical displacements, acts as a marker for identifying subsurface ramp structure (Fig. 3c). Surface uplift above the Chelungpu and Shihkang faults was distributed broadly in a zone of 5–20 km in width coeval with uplift above the ramp, and subsidence occurred east of the uplifted zone during the Chi-Chi earthquake. In other words, the area of coseismic topographic subsidence approximates the location of the inferred detachment. Carena et al. (2000, 2001) used small earthquakes to develop a 3D image of the major currently active faults in western Taiwan, delineated a major nearly horizontal detachment at a depth of about 10 km under the Central Range, and interpreted that several thrust faults, ramp up the detachment at the western uplifted zone. Based on our data, we also propose that the Chelungpu fault ramps up under the Western Foothills and then merges eastward into a detachment under the Central Range. Actually, the subsided area has been undergoing extension, forming several intermountain basins since the Late Quaternary, such as the Puli, Yuchih, Sun-Moon Lake, Tousher, and Tungkuei basins (Fig. 3a).

Conclusions

The extensive geodetic and geologic observations associated with the Chi-Chi earthquake provide an extensive database to evaluate controls of fault geometry on earthquake characteristics. The Chi-Chi earthquake ruptured two faults, the Chelungpu and Shihkang, tracing about 100 km in length in front of the Western Foothills. Based on the seismic information and geologic analysis by field measurement, we proposed that the coseismic deformation could be divided into two different structural domains along the two
The rupture during the Chi-Chi earthquake was initially concentrated in the Chelungpu fault associated with westward pure thrusting. The fault rupture later propagated northward, with northwest left-slip oblique thrusting along the Shihkang fault. We propose to discriminate between the two structural domains that can be advanced in seismic studies of the Chi-Chi earthquake to understand earthquake properties. At present, most seismic studies are at least consistent with the two structural domains description.

The GPS measurements on the upthrown block display an uplifted zone in the Western Foothills and subsided zone in the Central Range. We propose that thrust-fault features of the ramp and detachment structures have directly contributed to the vertical deformation in fold-and-thrust belts. The uplifted area is believed to be responsible for ramp structure. Particularly, this thrust fault by the recent finding shows a shallow-dipping seismic zone beneath the Central Range that may represent a detachment fault. In addition, our analysis of this major earthquake shows the importance of fault-ramp geometry in understanding the nucleation of the Chi-Chi earthquake. We suggest that large earthquakes on thrust ramps may be common in active fold-and-thrust belts. If we can identify subsurface fault ramps utilizing seismicity and GPS measurements, it would be important for accurate seismic hazard evaluation in such areas.

Figure 6. Map showing the major aftershocks of the Chi-Chi earthquake sequence and the near-source area seismicity before (brown dots) and after (blue dots) the Chi-Chi earthquake. Prior to the earthquake, the hanging wall of the rupture stayed relatively aseismic for a considerable time span. The data plotted on this map are from March 1991 to May 2000.

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References


Chiu, H. T. (1971). Folds in the Northern Half of Western Taiwan, Petrol Geol. Taiwan. 8, 7–19.


