Vol 444|23 November 2006|doi:10.1038/nature05253

nature

Slip zone and energetics of a large earthquake from the Taiwan Chelungpu-fault Drilling Project

Kuo-Fong, Ma[1], Hidemi Tanaka[2], Sheng-Rong Song[3], Chien-Ying Wang[1], Jih-Hao Hung[1], Yi-Ben Tsai[1], Jim Mori[4], Yen-Fang Song[5], Eh-Chao Yeh[6], Wonn Soh[6], Hiroki Sone[7], Li-Wei Kuo[3] & Hung-Yu Wu[1]

Determining the seismic fracture energy during an earthquake and understanding the associated creation and development of a fault zone requires a combination of both seismological and geological field data[1]. The actual thickness of the zone that slips during the rupture of a large earthquake is not known and is a key seismological parameter in understanding energy dissipation, rupture processes and seismic efficiency. The 1999 magnitude-7.7 earthquake in Chi-Chi, Taiwan, produced large slip (8 to 10 metres) at or near the surface[2], which is accessible to borehole drilling and provides a rare opportunity to sample a fault that had large slip in a recent earthquake. Here we present the retrieved cores from the Taiwan Chelungpu-fault Drilling Project and identify the main slip zone associated with the Chi-Chi earthquake. The surface fracture energy estimated from grain sizes in the gouge zone of the fault sample was directly compared to the seismic fracture energy determined from near-field seismic data[3,4]. From the comparison, the contribution of gouge surface energy to the earthquake breakdown work is quantified to be 6 per cent.

The North–South-trending Chelungpu fault is a major 90-km structure that dips shallowly to the east (30°), and principally slips within, and parallel to, bedding of the Pliocene Chinshui shale[5]. Taiwan Chelungpu-fault Drilling Project (TCDP) drilled two vertical holes 40 m apart (hole A to a depth of 2 km, and hole B to a depth of 1.3 km), and a side-track from hole B (hole C) at the depth of 950 m to 1,200 m about 2 km east of the surface rupture, near the town of DaKeng (Fig. 1a). The subsurface location of the Chinshui shale was known from high-resolution seismic reflection profiles[6,7] at a depth of about 1,000 m under the DaKeng site. The spatial slip distribution for the earthquake was well constrained from close strong motion stations and Global Positioning System (GPS) data[3,4] and shows a slip of 8.3 m on the fault near the drill site. The drilling carried out continuous coring for depths of 500–2,000 m for hole A, 950–1,300 m for hole B and 950–1,200 m for hole C, respectively. Geophysical well logs were carried out in hole A to collect seismic velocities, densities and digital images.

From the hole-A core, the Chelungpu fault zone is seen within the Chinsui shale as a damaged zone at depths of about 1,105 to 1,115 m, consisting of fault breccia and fault gouge (Fig. 1b). The degree of fracturing increases from the top to the bottom of the zone. Near the bottom of the broad zone of deformation, a 12-cm-thick primary slip zone (PSZ) can be identified based on the presence of ultra-fine-grained fault gouge and increased fracture density at depths of 1,111.23 to 1,111.35 m. A corresponding feature was also found in the hole-B core at depths of 1,136.50 to 1,136.62 m, confirming the fault dip of 30° E. The geophysical logging measurements of low seismic velocities and low electrical resistivity around the depth of 1,111 m also confirm that this is the main fault zone.

The PSZ seen in the core from hole C after splitting and polishing (Fig. 1c), shows several layers of slip zones associated with several repeating earthquakes. The individual slip zone has a thickness of about 2–3 cm with a 5-mm ultrafine grain zone in the bottom as indicated in the PSZ schematic (Fig. 1c). Among the slip zones, the least deformed region, which has the fewest number of cross-cutting cracks, is the 2-cm zone at the bottom of the PSZ, suggesting that this narrow band might be the major slip zone (MSZ) that corresponds to the Chi-Chi earthquake. Other estimates of the thickness for the slip zone from nearby sites are 50–300 μm observed at the surface near the DaKeng drill site[8], and 7 mm from a fault core at a depth of 330 m in shallow drilling before TCDP[9]. These determinations of slip zone thicknesses are all from layers located near the bottom of the fracture zone. The variation of thickness of the slip zone at different depths might correspond to differences in normal stress[10–12].

We also analysed the grain size distribution of the slip zone[13,14] using transmission electron microscope (TEM), scanning electron microscope (SEM) and optical microscope measurements, to estimate the surface fracture energy associated with the gouge formation. The distribution of particle size is shown in Fig. 2a, which follows a power-law distribution with a slope of about 2.3 (refs 15 and 16; see Supplementary Information). Grain sizes of 50 nm–100 mm (Fig. 2b, Supplementary Fig. 1a–c) were observed for the 2-cm MSZ (Supplementary Table 1). We consider grain sizes larger than 50 nm for the surface fracture energy calculation. The images with grain sizes of less than 50 nm show rounded shapes, suggesting that those small grains might be the result of precipitation rather than fracturing (Fig. 2b). Assuming spherical grains and a ratio of surface area to volume for spheres of 3/radius (ref. 13), we obtained the total particle surface area for the 2-cm slip zone S_{MSZ} of $6.46 \times 10^5\ \mathrm{m}^2$ per metre squared area. The mineral composition from X-ray diffraction for semiquantitative analysis shows that the MSZ was composed of about 70% of quartz, 5% of feldspar, and 25% of clay minerals (Supplementary Fig. 2). This gives a specific fracture energy G_c of about $1\ \mathrm{J\,m^{-2}}$ (refs 17–19). Using a correction for grain roughness λ of 6.6 (ref. 20), and the specific fracture energy, we obtain the surface fracture energy G_{MSZ} of the 2-cm MSZ by:

$$G_{\mathrm{MSZ}} = S_{\mathrm{MSZ}} \lambda G_c \qquad (1)$$

From equation (1), we obtain a value of $4.3\ \mathrm{MJ\,m^{-2}}$ for the surface fracture energy. This is interpreted as the minimum amount of energy that is necessary to produce the MSZ in one earthquake.

---

[1]Department of Earth Sciences, National Central University, Chung-Li 32054, Taiwan. [2]Department of Earth and Planetary Sciences, University of Tokyo, Tokyo 113-0033, Japan. [3]Department of Geosciences, National Taiwan University, Taipei 10617, Taiwan. [4]Disaster Prevention Research Institute, Kyoto University, Kyoto 611-0011, Japan. [5]National Synchrotron Radiation Research Center, Hsinchu 30076, Taiwan. [6]Kochi Institute for Core Sample Research, Agency for Marine-Earth Science and Technology, Kochi 783-8502, Japan. [7]Department of Geology and Mineraology, Kyoto University, Kyoto 606-8501, Japan.