Fracture Energy of a Large Earthquake from the Taiwan Chelungpu Fault

Earthquake associated with the seismic faulting is the most dangerous and unforeseen natural disaster. The 1999 magnitude 7.7 earthquake in Chi-Chi Taiwan, induced by Chlungpu faulting, produced very large surface displacement and caused huge casualty. Recovering deep cores which penetrate the fault zone is essential for studying the physical fault structure. Cores from the region of large slip on Chelungpu fault provides us a unique opportunity of sampling the fault in a recent earthquake. The energy budget of the earthquake has attracted the attention of the geoscience's disciplines for understanding the mechanism of earthquake nucleation and transition. We measured the particle size distribution for the particle diameter range from several nm to 150 µm of the major slip zone by using transmission electron microscope (TEM), transmission X-ray microscope (TXM), scanning electron microscope (SEM), and optical microscope (OM). We identify the power law of the distribution and ascertain the surface fracture energy. Comparing the fracture energy with the breakdown work, we obtain the fraction of the process of grain formation to the value of the earthquake breakdown work. The results may ascertain the implication of the nucleation, growth and transition structure of the fault zones.

Earthquake attracts much attentions because it is the most disastrous and unpredictable hazards in the world. The large earthquake events occurred in history, such as Tokyo, San Francisco, Tanshan and Kobe earthquakes, caused severe casualty and destruction to society. Taiwan is located at the complexity with the oblique collision zone of the Eurasian continental plate and the Philippine Sea plate which is moving WNW at about 70 mm per year. The mountain-building process is still in progress and a dominant collision zone, which induces folding and fault thrusting, exists in west-central Taiwan. In the last centuries, rapid crustal movement and widely distributed active structures induced tens of large earthquakes with magnitudes of over 7.0. The 1999 magnification 7.7 Chi-Chi earthquake struck near the town of Chi-Chi in Nantou County in west-central Taiwan, with its epicenter about 15 km east of the surface trace of the thrust fault and a hypocenter depth of about 10-12 km. It produced very large surface rupture of 80-90 km along the Chelungpu fault. In the south part of the fault, the vertical offsets was 2 m and increased to 8-10 m in the north, which is the largest offset ever measured for modern earthquake. Figure 1 shows the 8 m vertical

Beamline

01B X-ray Microscopy

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Fig. 1: 8m vertical offset on the Chelungpu fault created this new waterfall where the fault crossed the Tachia River.

offset of the fault created a new waterfall where the fault crossed the Tachia River. The slip displacement reached 12 m at the depth of 1 km. This earthquake is one of the largest inland events in the past century, which destroyed more than 100,000 buildings and results grave injury. The expectation of this work is to understand the physics, mechanism and controlling factors of the large earthquake. The final goal is to alleviate the potential disaster of seismic events in the future.

Grain rupturing and gouge formation are found to exist in brittle faults at all scales. This fine-grain gouge is believed to govern earthquake instability. Thus investigating the gouge texture property is very important to an understanding of the earthquake process. The actual thickness of the zone that slips during the rupture of a large earthquake is a key seismological parameter in understanding energy dissipation, rupture processes and seismic efficiency. The energy budget of the earthquake is another critical parameter which attracts the attention of the geoscience's disciplines for investigating the mechanism of earthquake. The characterization of particle size distribution, porosity and 3D structure of the fault rocks in transition from the fault core to damage zone are related to the comminuting, fluid behaviour and energy in the earthquake faulting. The results will reveal the insight of the mechanism of faulting, the nucleation, growth, transition structure and permeability of the fault zones.

Recovering deep cores which penetrate the fault zone is essential for studying the physical fault structure. Fault zone rocks are extremely fragile and easily altered by weathering; therefore, the surface outcrops can provide only limited information. The Taiwan Chelungpu-fault Drilling Project (TCDP) has drilled three deep holes into the slip and fault zones of the Chelungpu fault. Cores from the region of large slip on Chelungpu fault provides us precious materials to study the characteristics, mechanism and energy budget in a recent thrust fault. The Chelungpu fault is major 90 km structure that dips shallowly the east (30˚) and slips within bedding of the Pliocene Chinshui Shale. The TCDP drilled two vertical holes 40 m apart (hole A and hole B) and a side-track from hole B (hole C) near the town of Dakeng (Fig. 2). The drilling carried out continuous coring for depths of 500-2000 m for hole A, 950-1300 m for hole B and 950-1200 m for hole C, respectively. Geophysical well logs were carried out from hole A to collect seismic velocities, densities and digital images.

Chelungpu fault zone is within the Chinsui shale as a damaged zone at depth of 1105 to 1115 m observed from hole A core. The degree of fracturing increased from the top to the bottom of the damaged zone. Near the bottom of the deformation zone, we identify a 12-cm-thick primary slip zone (PSZ) based on the presence of ultra-fine-grained fault gouge at depths of 1111.23 to 1111.35 m. The geophysical logging measurements of low seismic velocities and low electrical resistivity around the depth of 1111 m also indicate that this is the primary fault zone. The PSZ consists of several layers of slip zone associated with several repeating earthquakes. Each zone has a ~2 cm thickness, indicating the number of earthquake events is 6. Among the slip zones, the least deformed region, which has the fewest cross-cutting cracks, is the 2-cm zone at

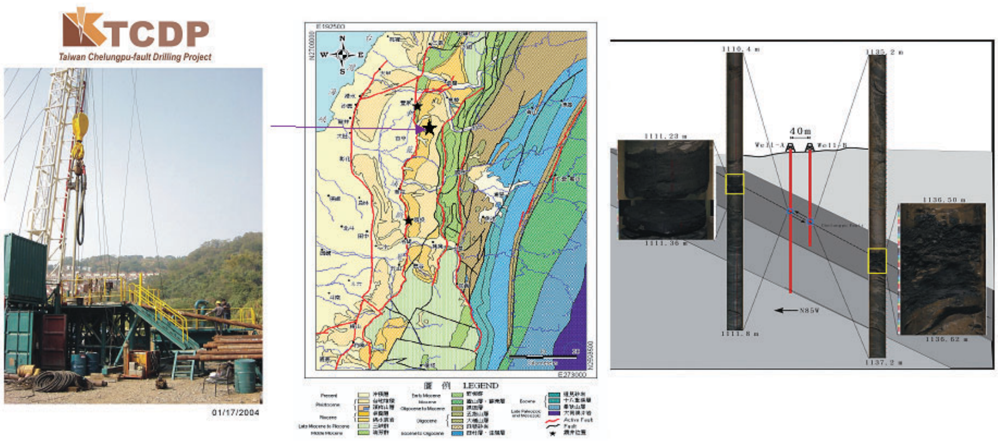

Fig. 2: Taiwan Chelungpu-fault Drilling Project drilled two vertical holes 40 m apart (hole A and hole B) and a side-track from hole B (hole C) near the town of Dakeng.

the bottom of the PSZ. This narrow band might be the major slip zone (MSZ) which corresponds to the Chi-Chi earthquake.

Several models were proposed to describe the energy budget for physical process of earthquake slip. In the common usage slip-weakening model, the elastic strain energy which released during an earthquake is distributed between the frictional heat, E_H, the product of fault area and seismic fracture energy, E_G, and the energy radiated as seismic waves, E_R. The frictional heat is a large component of the total energy budget, but it does not directly affect earthquake rupture dynamics. Whereas the radiation efficiency, η_R, which is the ratio of the radiation energy to the energy available for mechanical processes, defined as $\eta_R = E_R/(E_R + E_G)$, plays a significant role. For the mature earthquake, the energy spent for gouge formation is small, η_R is nearly equal to 1. The surface fracture energy associated with gouge formation is a form of latent heat required to produce an earthquake rupture surface and related to parameters controlling rupture propagation and processes of slip weakening. It describes the flow of energy at rupture tip which is required to create a rupture surface and produce a breakdown in strength. Formation of the slip zone is associated with the seismic fracture energy, which is consumed as the earthquake rupture propagates. The surface fracture energy for the creation of small grains is a contribution, but may not be the total equivalent to the seismic fracture energy. The breakdown work is the excess work over some minimum level achieved during slip and is the energy spent to allow the rupture to advance. The breakdown work is composed of the surface fracture energy for gouge formation and other dissipative losses during faulting. It can be considered as an equivalent to the seismic fracture energy per unit area. Comparing the surface fracture energy with the breakdown work, we will know the relation of the energy for processing the grain formation to the value of the earthquake breakdown work. The results would provide the information to confirm the surface fracture energy and energy budget in the 1999 Chi-Chi earthquake.

The total fracture surface area, S_T, which includes the surface area of cataclastic particles in the ultracataclasite, S_{UC}, surface area of gouge particles in subsidiary faults of the damage zone, S_{SF}, and surface area of microfracture damage area, S_{MF}. We analysis the particle size distribution and the structure of the fault core gouge by transmission electron microscope (TEM), scanning electron microscope (SEM), nano-transmission X-ray microscope (TXM), and optical microscope (OM) for the particle diameter range from several nm to 150 μm to determine the facture surface area in the ultracataclasite associated with the gouge formation (S_{UC}) of MSZ. The Chelungpu fault is a 10 m thick zone of fractured rock containing 1 m thick core of sheared cataclasite and ultracataclasite. The primary slip zone is 12 cm thick. The ultracataclasite layer of MSZ is 2 cm thickness. The components of the drilling gouge include smectite, illite, chlorite and kaolinite. Figure 3 shows the 2D phase contrast images of the TXM of hole A fault core gouge of MSZ. The particle size distribution of the ultracataclasite from all images is shown in Figure 4, which is consistent with the power law $N(D) = aD^{-b}$, where D is particle diameter, N(D) is the number of particles for each size diameter per unit area (mm^2), and constants a = 0.005, b = 2.3. The grain size for calculating the surface area of ultracataclasite is from 50 nm to 150 μm for MSZ. The upper cut-off grain size of 150 μm is obtained by adopting optical microscope. From the particle size observation using transmission electron microscope, we consider the lower cut-off of the particle size is 50 nm. The images with grain sizes of less than 50 nm shows rounded shapes, suggesting that those small grains might be the results of precipitation rather than fracturing. The

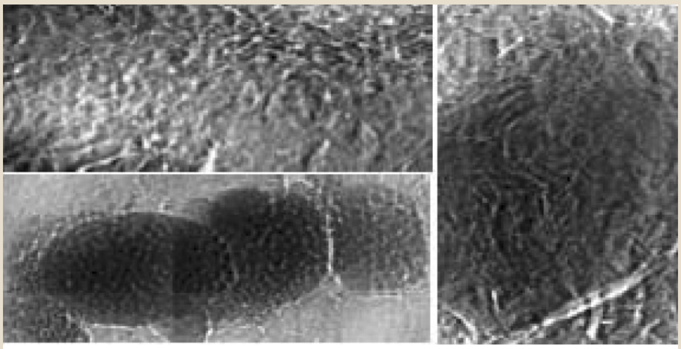

Fig. 3: TXM 2D phase contrast image of the hole A gouge within major slip zone.

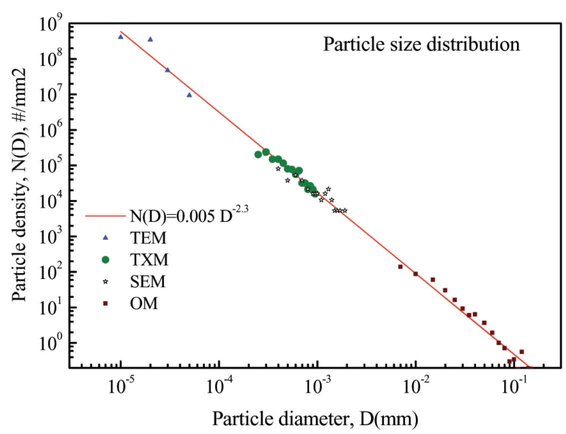

Fig. 4: Particle size distribution measured by using TEM, TXM, SEM and OM from the gouge of hole A within major slip zone.

total fracture surface area for 2 cm MSZ from hole A core is 5.5 x 10^5 m^2/m^2 supposing the spherical grains. Assuming free-surface energy is 1 J/m^2, and the geometric surface should be increased by about a factor of 6.6 to account for non-spherical grains shapes, we obtained a value of 4.0 MJ/m^2 for surface fracture energy in MSZ. The estimated number of events is 6. The contribution of gouge surface energy on one earthquake event in MSZ to earthquake breakdown work (11.6 M J/m^2) is quantified to be 6 %. This value shows that the process of grain formation represents about 6 % of the earthquake breakdown work. We consider this estimate to be the maximum assuming that there is no fracture energy occurred during sliding. The residual part of the breakdown work probably is heat associated with other dynamics processes, such as fault thermo-pressurization or fault lubrication.

The surface fracture energy of gouge zone of the Chelungpu fault for the Chi-Chi earthquake is identified about 6% of the breakdown work. The calculated value of radiation efficiency η_R is 0.88, which is intermediate between that of well-developed Punchbouwl fault in Californiea (η_R is nearly 1) and that of the new fractured earthquakes in the South African mine (η_R is 0.16). The physical differences in the fault zones depend on the maturity and style of faulting and result the differences in the mechanical energy absorbed during large events. When large earthquakes occur on mature fault, there is less fracturing, so the proportional amount of dissipative energy is smaller, compared to the more fracturing behaviour of young faults.

The investigation of energetic budget of the fault zone gauge is pivotal for understanding the earthquake process. The results of the particle size distribution measurement and analyzing would reveal the insight of the surface fracture energy and the relation with the energy budget in the 1999 Chi-Chi earthquake, then apply to analyze other faulting events and to ascertain the fracture mechanics of thrust fault system. Furthermore, it may understand the relation of the nucleation, growth and transition structure of the fault zones and then deduce the mechanism of faulting, and the nucleation of the earthquake.

Experimental Station

Nano-transmission X-ray microscopy

Publication

K. F. Ma, H. Tanaka, S. R. Song, C. Y. Wang, J. H. Hung, Y. B. Tsai, J. Mori, Y. F. Song, E. C. Yeh, W. Soh, H. Sone, L. W. Kuo and H. Y. Wu, Nature, **444**, 473 (2006).

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