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Benefits of Defining Geological Sensitive Zones in the Mitigation of Disasters Along Earthquake Fault Zones in Taiwan – The Case of Milun Fault

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In Taiwan, the main purpose of earthquake fault zone legislation is to prevent earthquake-related disasters around the surface traces of active faults, particularly in urban areas. Here, the Geologically Sensitive Area (GSA) of the Milun Fault (Milun Earthquake Fault Zone) is used as an example to reveal the importance of such legislation. Field data collected along the Milun Fault before and after the 2018 Hualien Earthquake were used to reveal the reappearance of damages within the GSA. The 2018 Hualien Earthquake represents one of the shortest recurrence intervals (67 years) among all major faults in Taiwan. Most of the surface ruptures and damaged buildings in Hualien City were within the Milun Fault GSA and concentrated on the hanging wall of the fault. Moreover, 61% (91/148) of the damaged buildings and 83% (692/835) of the surface ruptures occurred within 100 m of the fault line. The results of this study demonstrate the importance of defining GSAs of active faults for mitigating earthquake hazards.

Keywords: earthquake fault zone, surface rupture, Milun Fault, Taiwan

1. Introduction

Co-seismic surface ruptures may lead to damage to buildings and facilities on or close to an active fault [1–4]. Defining earthquake fault zones (EFZ) is very important for urban planning, as almost no structures can sustain deformations induced by surface ruptures [5]. This is known as Surface Fault Rupture Hazard (SFRH). Such hazards can be avoided if detailed maps of EFZs are drawn. In California, USA, a law to restrict development within EFZs was enacted in the early 1970s. The Alquist–Priolo Earthquake Fault Zoning Act (California Geological Survey) requires state geologists to establish EFZs around the surface traces of active faults [6]. To grant a construction permit, a geological investigation is required and the site must be more than 50 feet away from a fault line/zone [7].

Since the 1999 Chi-Chi Earthquake, the Taiwanese government has paid attention to the damage caused by co-seismic surface ruptures. The epicenter of the Chi-Chi Earthquake, which occurred at 01:47 local time on September 21, 1999, was close to Chi-Chi Town in Nantou County. The earthquake struck central Taiwan with a magnitude of 7.6, resulting in 2,415 fatalities and 11,000 injuries [8, 9]. The displacement of the Chelungpu Fault, which caused the earthquake, ranged from a few centimeters to 10 m. Ground deformation was concentrated in a relatively narrow zone along the primary fault scarps on the hanging wall, with little or no geological deformation on the footwall [10]. Field investigations indicated that most structures collapsed or were damaged owing to severe ground deformation along or near the fault lines [11]. Examples of surface ruptures and the resulting damage to the structures are shown in **Figs. 1** and **2**. A study on human fatalities in the near-fault regions of the earthquake [12] showed that the death rate among residents in the hanging-wall areas was significantly higher than that among residents in the footwall areas, especially within a few hundred meters on either side of the Chelungpu Fault (**Fig. 3**). After the earthquake, the Central Geological Survey (CGS) began systematically surveying active faults in Taiwan. Methods and techniques for locating active faults include morphological analysis, field survey, geophysical investigation, structural characterization, geological drilling, trench excavation, global positioning systems (GPS), and leveling surveys. Consequently, $1:25,000$ geological maps of 33 active faults have been produced to date (**Fig. 4**).

Once the Geology Act was enacted in 2010 in Tai-

Fig. 1. Looking northward along the surface rupture at Kuangfu Middle School, around the central part of the Chelungpu Fault, there is steep scarp face on the hanging wall over the footwall (October 1999).

Fig. 2. Damaged buildings above the fault scarp near Chung-Cheng Park, along the northern part of the Chelungpu Fault (October 1999).

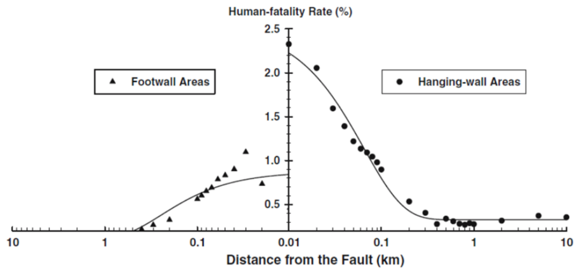

Fig. 3. Human-fatality rates versus distances from the surface trace for the hanging-wall and the footwall areas along the Chelungpu Fault (modified from Pai et al. [12]).

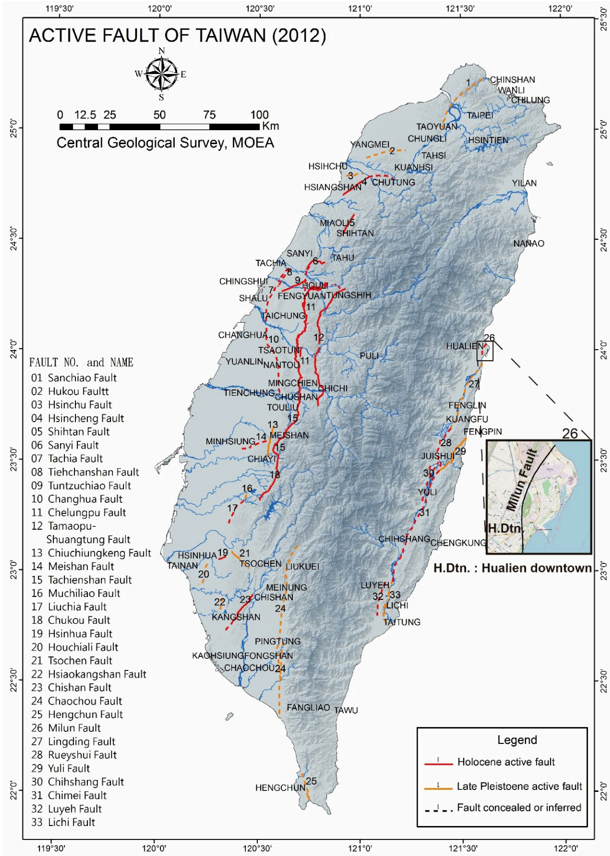

Fig. 4. A total of 33 active faults have been determined by CGS [13]. Note that the Milun Fault is numbered 26.

wan [14], geologically sensitive areas (GSA) were defined for active faults by the CGS, based on the experience of the 1999 Chi-Chi Earthquake and the extent of the damage along the Chelungpu Fault. The GSA for an active fault with a reverse component is 200 m in width from the fault trace on the hanging wall and 100 m in width on the footwall. The GSA of a pure strike-slip active fault is 100 m in width on both sides of the fault trace. The first GSA of an active fault was announced on March 28, 2014 (**Fig. 5**).

The Geology Act states that the government of Taiwan shall declare any site that is vulnerable to geological disasters triggered by an active fault as a GSA. Within the GSA of an active fault, a building permit is granted only after both accredited geological investigations and a geological safety assessment are conducted [14].

The EFZ Act of California regulates construction with the objective of preventing hazards on or adjacent to an active fault. It has been almost five decades since this law was enacted. However, owing to long earthquake recurrence intervals, ranging from several hundred years to several thousand years, none of the designated EFZs have been tested by a significant earthquake event. In this study, the Milun Fault GSA in Taiwan was used as an example to demonstrate how a GSA can effectively capture the extent of disasters.

2. Hualien Earthquake and Milun Fault

2.1. Hualien Earthquake

At 23:50 (UTC+8) on February 6, 2018, eastern Taiwan was struck by an intense earthquake of magnitude 6.4 on the moment magnitude scale [15]. The entire Taiwan Island experienced shaking and the city of Hualien suffered tremendous damage, including five collapsed buildings, 148 severely damaged buildings, and numerous slightly damaged buildings. According to the Taiwan Central Weather Bureau (CWB), the hypocenter of the earthquake was on the offshore segment of the Milun Fault (24.10°N, 121.73°E) at a depth of 6.31 km. The ac-

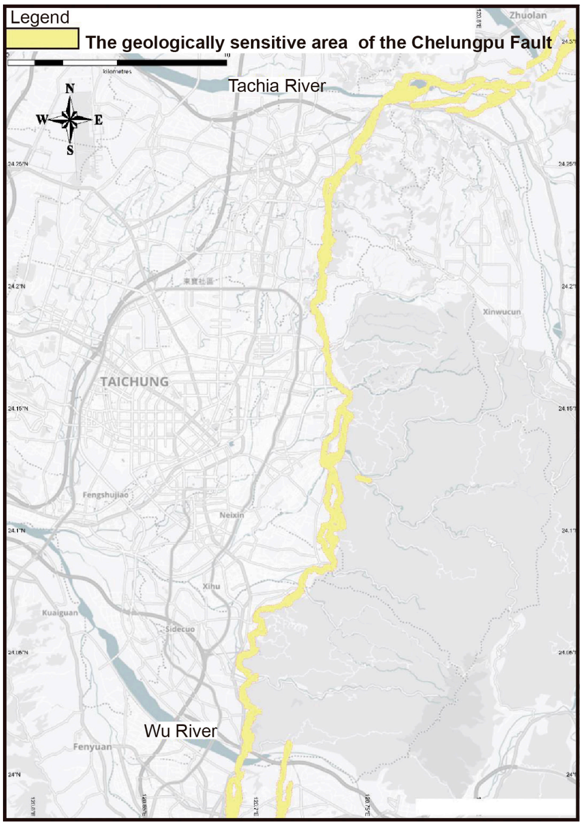

Fig. 5. GSA of the Chelungpu Fault north of the Wu River. The width of this area is approximately 300 m, including 100 m on the footwall and 200 m on the hanging wall.

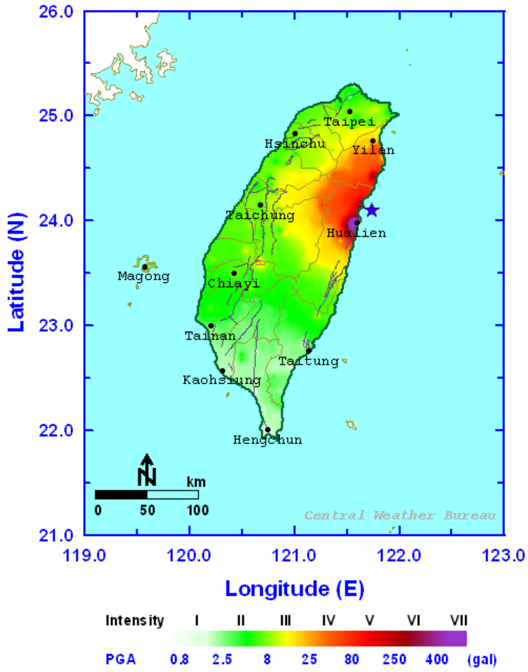

Fig. 6. Earthquake intensity map of the February 6, 2018 M_w 6.4 event. Hualien is a regional hub and the largest city along Taiwan's east coast [16]. The black lines on land denote active faults.

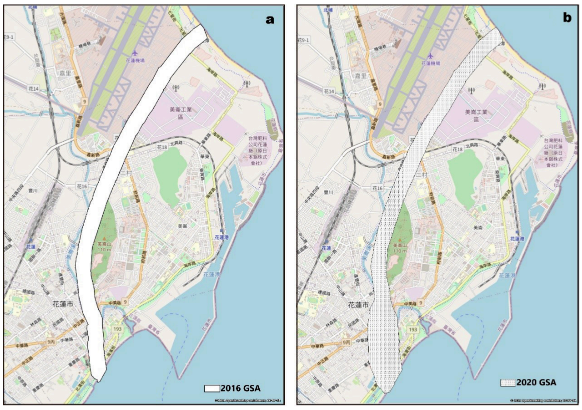

Fig. 7. Milun Fault GSA. CGS released the first version of the Milun Fault GSA in 2016 (a) and the revised version in 2020 (b). There is a 0.5 km^2 area of increase in the revised version, mainly in the southern section.

tivation of the Milun Fault produced surface ruptures on land extending from the coast in the north southeastward to downtown Hualien City (**Figs. 4** and **6**). This earthquake led to 17 deaths, nearly 300 injuries, and economic losses of more than 8 billion NT dollars [17].

Before this event, the only recorded strong earthquake on the Milun Fault was the 1951 Hualien Earthquake, which struck on October 21 that year with a magnitude of 7.3 [18, 19]. Thereafter, two earthquakes of magnitude larger than 7.0 occurred on the same day. These earthquakes led to the deaths of 85 people and the collapse of or damage to more than 40% of the buildings in Hualien City [18, 19]. The 2018 Hualien Earthquake occurred approximately 67 years after the 1951 earthquake sequence.

2.2. Milun Fault

The Milun Fault is a largely N35°E trending fault, with a length of 23.3 km [20], only approximately 8 km of which is on land [21] and located in Hualien County. The northeastern end of the terrestrial section can be traced from the coast in the north southwestward into downtown Hualien City (**Fig. 4**) [22, 23]. It is a left-lateral strike-slip active fault with a reverse component [24]. The last major rupture on the Milun Fault was in October 1951, which produced an approximately 1.2 m vertical offset and an approximately 2 m left-lateral horizontal offset [25, 26]. The 2018 earthquake produced a similar rupture pattern with smaller displacements of a 70 cm horizontal offset and a 50 cm uplift [26]. The strong similarities in the fault-rupture pattern and kinematic behavior show that the 2018 event is a reactivation of the Milun Fault.

2.3. Milun Fault GSA (Milun Earthquake Fault Zone)

There were traceable surface ruptures along the Milun Fault from the 1951 Hualien Earthquake. The first public announcement of the Milun Fault GSA (**Fig. 7a**) was made on December 21, 2016, by the CGS. The 2018 Hualien Earthquake provided new evidence of the sur-

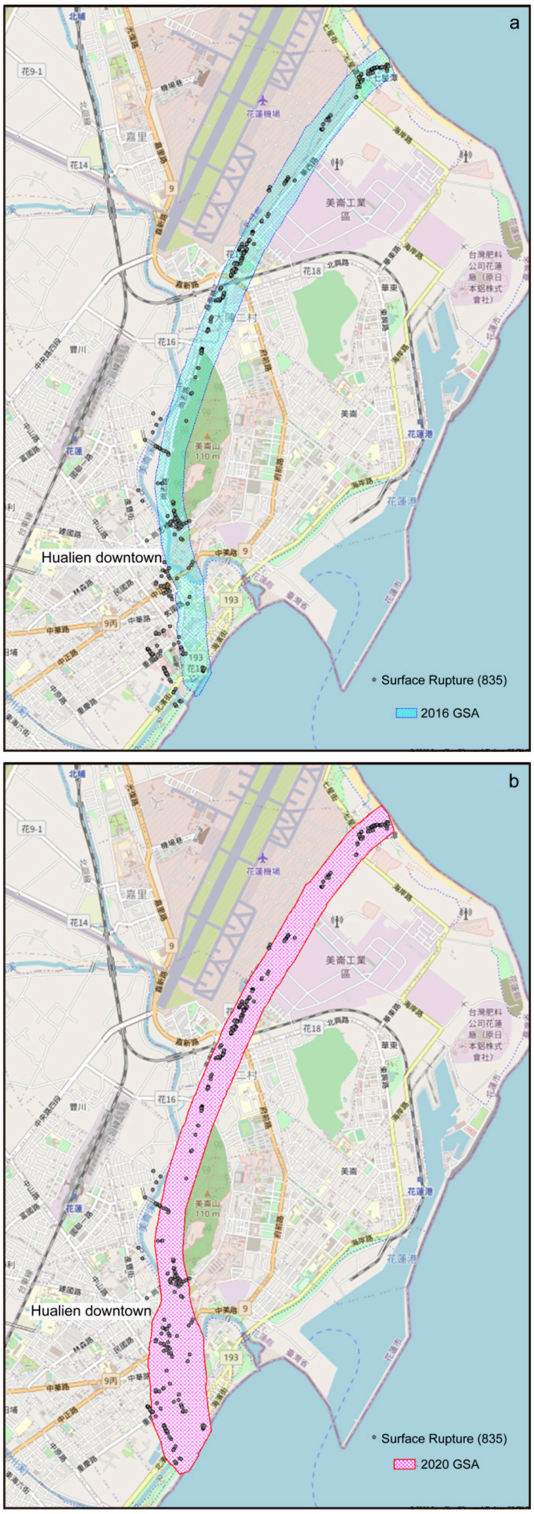

Fig. 8. Locations of surface ruptures from the 2018 Hualien Earthquake, indicated by circles, and the Milun Fault GSA. Map (a) is of the 2016 version of Milun Fault GSA. Map (b) is of the 2020 revised version.

face ruptures of the Milun Fault. A revised version of the Milun Fault GSA was announced on April 28, 2020 (**Fig. 7b**).

Table 1. Distributions of damaged buildings and surface ruptures of the 2018 Hualien Earthquake.

Types	2016 GSA (**Quantity**)	2020 GSA (**Quantity**)
Surface ruptures inside the GSA	647	780
Surface ruptures outside the GSA	188	55
Damaged buildings inside the GSA	100	132
Damaged buildings outside the GSA	48	16
Collapsed buildings inside the GSA	2	2
Collapsed buildings outside the GSA	3	3

Source: 20180206 Hualien Earthquake and Geological Survey Report from CGS [27].

2.4. Surface Ruptures and the GSA

After the 2018 Hualien Earthquake, the CGS conducted detailed investigations of the surface rupture characteristics and locations, as well as the domains of the flanks susceptible to fault action [27]. Two of the authors of this study were involved in these investigations. The surface ruptures induced by the Milun fault were identified based on their structural patterns, such as fracture modes, continuity, and trend. There were 835 surface rupture sites along the Milun Fault, with individual ruptures ranging from a few centimeters to tens of meters. Among them, 77% (647/835) were in the 2016 GSA and 93% (780/835) were in the 2020 GSA (**Fig. 8** and **Table 1**).

2.5. Building Damage and the GSA

The CGS also investigated the distribution of damaged buildings. There were 148 lightly or moderately damaged buildings and, five collapsed buildings along the Milun Fault (**Fig. 9**). Among the damaged buildings, 68% (100/148) were within the 2016 GSA and 89% (132/148) were within the 2020 GSA (**Table 1**).

Some collapsed buildings were not within the GSA, but west of its western boundary (**Fig. 9**). Perhaps these collapses resulted from foundation failure due to liquefaction of the alluvial sediments along a paleochannel.

2.6. Results

Prior to the 2018 Hualien Earthquake, the previous major surface ruptures along the Milun Fault were caused by the M 7.3 earthquake event in October 1951. As the interval between these two events was relatively short, they provide critical information for delimiting the GSA and verifying its effects.

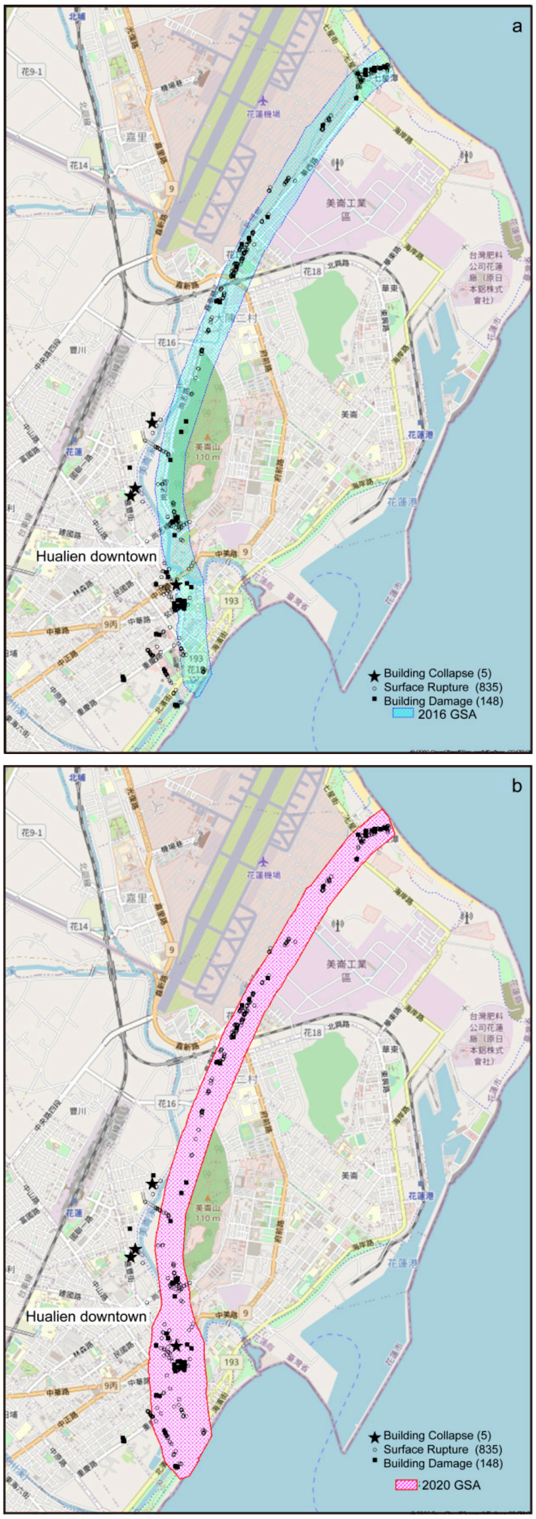

Fig. 9. Distribution of buildings damaged during the 2018 Hualien Earthquake. Map (a) is of the 2016 version of Milun Fault GSA. Map (b) is of the 2020 revised version.

The surveys following the 2018 Hualien Earthquake showed that most of the surface ruptures and damaged buildings in Hualien City were within the Milun Fault GSA (**Fig. 9**). There was more damage on the hanging wall than on the footwall, and toward the fault line (**Table 2** and **Fig. 10**). This distribution pattern was compatible with the occurrence of surface ruptures (**Table 3** and **Fig. 11**). These findings revealed that GSAs of active faults are necessary and crucial for protecting human habitats from earthquake disasters, or at least mitigating the risk of severe damage.

Table 2. Number of damaged buildings versus distance intervals from the Milun Fault.

Distance interval [m]	Damaged buildings (Quantity)		
	Hanging wall	Footwall	Total
0–100	61	30	91 (61%)
100–200	19	0	19 (13%)
200–300	20	3	23 (16%)
300–500	2	13*	15 (10%)
Total	102 (69%)	46 (31%)	148 (100%)

*Buildings were damaged by ground liquefaction and shaking.
Source: 20180206 Hualien Earthquake and Geological Survey Report from CGS [27].

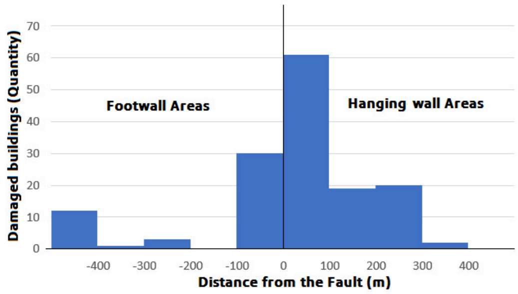

Fig. 10. Number of damaged buildings versus distance from the surface fault trace for the areas on the hanging wall and the footwall along the Milun Fault. Note that the damage to buildings at the far end of the footwall was caused by ground liquefaction and shaking.

3. Summary

Although many countries have established EFZ acts, EFZs have rarely been tested by contemporary earthquakes and their disaster mitigation effects are not yet clear. The 2018 Hualien Earthquake in Taiwan provided an excellent opportunity to examine the necessity of GSAs of active faults, which share similarities with EFZs in the USA. During earthquake events, surface ruptures and building damage may occur repeatedly in the GSAs. Studies on the relationship between surface ruptures and damage to human habitats can help in better defining GSAs and mitigating the exposure of humans to the potential risk of natural disasters.

Table 3. Numbers of surface ruptures versus distance intervals from the Milun Fault.

Distance	Surface ruptures (Quantity)		
interval [m]	Hanging wall	Footwall	Total
0–100	491	201	692 (83%)
100–200	61	43	104 (12%)
200–300	19	6	25 (3%)
300–500	14		14 (2%)
Total	585 (70%)	250 (30%)	835 (100%)

Source: 20180206 Hualien Earthquake and Geological Survey Report from CGS [27].

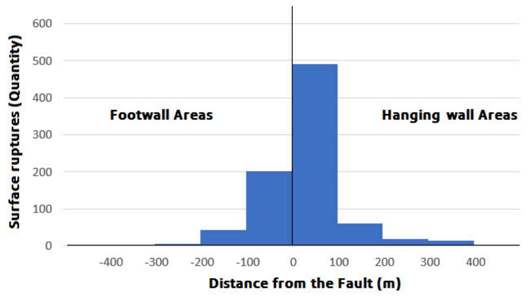

Fig. 11. Number of surface ruptures versus distance from the surface fault trace for the areas on the hanging wall and the footwall along the Milun Fault.

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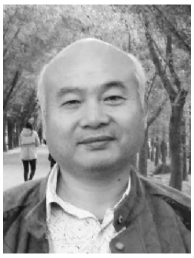

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