LUGU, TAIWAN SEPTEMBER 18, 2022, M_W 6.9 EARTHQUAKE

PRELIMINARY VIRTUAL RECONNAISSANCE REPORT (PVRR)

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PREFACE

The Earthquake Engineering Research Institute (EERI) is the leading non-profit membership organization that connects those dedicated to reducing earthquake risk. Its multidisciplinary members include engineers, geoscientists, social scientists, architects, planners, emergency managers, academics, students, and other like-minded professionals. EERI has been bringing people and disciplines together since 1948. The objective of the Earthquake Engineering Research Institute is to reduce earthquake risk by (1) advancing the science and practice of earthquake engineering, (2) improving understanding of the impact of earthquakes on the physical, social, economic, political, and cultural environment, and (3) advocating comprehensive and realistic measures for reducing the harmful effects of earthquakes.

Within EERI, this report has been produced by the Learning From Earthquakes (LFE) program. The mission of the LFE Program is to accelerate and increase learning from earthquake-induced disasters that affect the natural, built, social and political environments worldwide. This mission is accomplished through field, remote or hybrid reconnaissance, data collection and archiving, and dissemination of lessons and opportunities for reducing earthquake losses and increasing community resilience. For more information on LFE, please visit http://www.learningfromearthquakes.org/about.

ACKNOWLEDGMENTS

Conducting post-earthquake reconnaissance is critically important to observe, document and analyze the seismic performance of built and natural environments. While experimental work in the laboratory and analytical modeling are extremely valuable, we will continue to rely on post-earthquake reconnaissance for many years to come to learn about and understand the effects of earthquakes on full-scale three-dimensional structures in the field which provide the ultimate test of our progress in mitigating the effects of natural hazards on society. Hence, post-earthquake reconnaissance is at the very core of the missions of both the EERI's Learning From Earthquakes (LFE) program. This report is the result of hard swift work and contributions by a large number of individuals and organizations.

The sharing of videos, damage reports and briefings via WhatsApp by the entire EERI membership, the NHERI community in the United States as well as members of the earthquake engineering community in several countries was extremely helpful and much appreciated.

This material is based upon work by the Learning for Earthquakes Endowment Fund of the Earthquake Engineering Research Institute and by the National Science Foundation under Grant No. CMMI 1841667.

For more information about the Earthquake Engineering Research Institute please visit the EERI website: https://www.eeri.org/

In particular, for a full listing of resources including Virtual Earthquake Reconnaissance Team (VERT) reports, datasets, and publications for over 300 different earthquakes occurring in more than 50 countries during the last 70 years of EERI's Learning From Earthquakes program, please visit the EERI LFE earthquake archive: https://learningfromearthquakes.org/archive/table-view

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EXECUTIVE SUMMARY

On September 18th, 2022, at 2:44 pm local time, a moment magnitude 6.9 earthquake struck 42.7 km north of Taitung City, Taiwan. The epicentral coordinates reported by the U.S. Geological Survey (USGS, 2022a) and the Taiwanese Central Weather Bureau Seismological Center (Central Weather Bureau Seismological Center, 2022) were 23.159°N 121.316°E and 23.14°N 121.20°E, respectively. The USGS reported a hypocenter depth of 10.0 km, whereas the Central Weather Bureau Seismological Center reported a depth of 7.0 km. The earthquake was preceded by a magnitude 6.5 earthquake in the same area 17 hours earlier. There have been several earthquakes of magnitude 5.0 and larger in the sequence (USGS, 2022a).

Earthquake sequences with consequent large magnitude events separated by short time intervals have been occurring at different parts of the world in the past years (e.g., 2019 Ridgecrest earthquakes (Mosalam et al., 2019); 2022 Iran earthquake sequence (Mosalam et al., 2022)). From a structural engineering and design perspective, this is a reminder that strong pre-shocks and aftershocks (even with the same magnitude) can occur before and after the mainshock and their cumulative effects should be characterized and considered in the design codes of buildings and other infrastructure systems.

This earthquake caused some geotechnical failures and damage to infrastructure, mainly bridges, railroads, and highways. Damage to buildings was observed, but it was primarily concentrated on older non-ductile structures and non-structural component damage. At least one building collapsed and hundreds more had some damage. The earthquake resulted in at least one death and 171 earthquake related injuries.

The earthquake highlighted the vulnerabilities of older non-ductile concrete buildings in seismic regions, concrete bridges, and non-structural building components during an earthquake. This event also highlighted the importance of an earthquake early warning system.

1.0 Introduction

On September 18th, 2022, at approximately 2:44 pm local time, a moment magnitude (M_w) 6.9 earthquake struck 42.7 km north of Taitung City, in southeastern Taiwan. The epicentral coordinates reported by the U.S. Geological Survey (USGS, 2022a) and the Taiwanese Central Weather Bureau Seismological Center (Central Weather Bureau Seismological Center, 2022) were 23.159°N 121.316°E and 23.14°N 121.20°E, respectively, which corresponds with the Chishang township. The USGS reported a hypocenter depth of 10.0 km, whereas the Central Weather Bureau Seismological Center reported a depth of 7.0 km. A tsunami warning was triggered by this earthquake for Miyako Island in the East China Sea; however, it was later withdrawn.

The purpose of this Preliminary Virtual Reconnaissance Report (PVRR) is to provide a summary of the characteristics of the event, the seismicity of the impacted region, and an overview of the main effects of the earthquake as collected from publicly available information.

The earthquake was preceded by a magnitude 6.5 earthquake in the same area 17 hours earlier. There have been several earthquakes of magnitude 5.0 and larger in the sequence (USGS, 2022a). Earthquake sequences with consequent large magnitude events separated by short time intervals have been occurring at different parts of the world in the past years (e.g., 2019 Ridgecrest earthquakes (Mosalam et al., 2019); 2022 Iran earthquake sequence (Mosalam et al., 2022)). From a structural engineering and design perspective, this is a reminder that strong pre-shocks and aftershocks (even with the same magnitude) can occur before and after the mainshock and their cumulative effects should be characterized and considered in the design codes of buildings and other infrastructure systems.

This earthquake caused some geotechnical failures, specifically landslides. Infrastructure damage consisted of bridge damage and a trail derailment. Damage to buildings was observed, but it was primarily concentrated on older non-ductile structures. Non-structural damage was also observed for components within buildings, such as collapse of ceilings, shelving falling over, and items falling off shelves in stores.

1.1 Social Impacts

1.1.1 Casualties (Fatalities and Injuries)

There was one fatality and 171 injured people (中央通訊社, 2022). The death occurred due to the fall of heavy machinery in a cement factory in Yuli township in Hualien County (Li-yun et al., 2022). Earthquakes in Taiwan with higher death tolls include the 1999 M_w 7.7 Chi-Chi earthquake and the 2016 M_w 6.4 southern Taiwan earthquake, which caused more than 2,000 and 100 fatalities, respectively (Blanchard & Lee, 2022).

1.2 Affected Population

The earthquake was felt across Taiwan with reports of shaking in Taipei (Reuters, 2022). Combined, the total population exposed to strong, very strong, or severe intensities was 438,000.

The earthquake affects were most significant in the Chishang township, located in northern Taitung county (The Associated Press, 2022). The Chishang township consists of ten villages with a population of approximately 8,200 people.

1.3 Rescue and Relief

Within one day of the earthquake, 30 emergency rescue vehicles and 2,265 personnel had been deployed for rescue efforts across Taiwan (Li-yun et al., 2022). 110 soldiers were deployed in Hualien county alone, along the island's eastern coast, to assist with disaster relief efforts (Picheta & Cheung, 2022). Four people were rescued from a collapsed mixed-use three-story building in Yuli (the ground floor was a 7-eleven convenience store and two other stories were residential). Those that were rescued were the owner (70 years old), the owner's wife, a 39-year-old woman, and her 5-year-old daughter (Lai & Moritsugu, 2022). Figure 1.1 shows the 5-year-old girl being rescued from the collapsed building covered with blankets.

Figure 1.1. Rescue efforts from a collapsed mixed-use building.

Three people were rescued after their vehicle fell off a bridge that collapsed in southeast Taiwan. They were taken to the hospital for injuries but survived (Davidson & Associated Press, 2022). Due to roads blocked by landslides, more than 600 people were stranded in the mountain areas of Chike and Liushishi around Sixty Stone Mountain, which is in eastern Taiwan (公視新聞網, 2022). There were no injuries among the more than 600 stranded people and rescuers were working to reopen the roads. 20 passengers were evacuated after a train derailed at Dongli station due to debris hitting the train from a collapsed canopy (Picheta & Cheung, 2022). There were no casualties from the incident. 29 people in Hualien and 23 in Taitung were displaced due to the earthquake and are currently being housed in three different emergency shelters (Li-yun et al., 2022).

1.4 Building Damage

Much of the building damage occurred in the town of Chishang, in northern Taitung county and in Hualien county (Davidson & Associated Press, 2022). The building damage occurred in older non-ductile concrete buildings with a variety of uses, such as residential, schools, and mixed use. Non-structural damage was much more common for buildings across the region. This damage included items falling off shelves in stores, shelving falling over, and the collapse of ceiling systems. Section 4.0 summarizes building damage due to the earthquake.

1.5 Infrastructure/Power Loss

Power lines were destroyed by the earthquake around Chike Mountain leaving about 22,024 households in Yuli without power (Li-yun et al., 2022). As of Monday, September 19th, power had been restored to all but 445 households. Water pipe damage throughout Yuli was also reported causing 4,842 households to lose access to water in Hualien and Taitung (Huang Li-yun et al., 2022). On Monday, September 19th, 1,801 households still did not have access to potable water.

Debris from a falling canopy on a platform at Dongli railway station in Fuli hit a passing train, derailing six cars (Davidson & Associated Press, 2022).

The earthquake caused bridge and road damage throughout eastern Taiwan and ground subsidence of the ground. At least two bridges were reported damaged. These bridges were located in rural areas and caused tourists and residents to be trapped. Gaoliao Bridge in Hualien County collapsed with most damage occurring at its northern end at the Dongli section. The Siouguluan River Bridge, which is a railway bridge, was also heavily damaged due to the earthquake (CNA, 2022). A section of Provincial Highway 30, which connects Taitung's Changbin and Yuli townships was closed due to cracks and subsidence caused by the quakes (Li-yun et al., 2022).

Taiwan houses the largest production of semiconductors and advanced chips. As such, the September 18 earthquake, which affected several manufacturing facilities, led to the temporary suspension of production following the event (Trend Detail News, 2022). This can lead to further supply chain issues for the technology sector similar to the disruption that happened following the 1999 M_w 7.7 Chi-Chi earthquake. This earthquake demonstrated the importance of designing manufacturing facilities not only for life safety performance objectives, but also considering functional recovery performance objectives to prevent severe economic consequences. This is particularly important with the recent signing of the Creating Helpful Incentives to Produce Semiconductors (CHIPS) and Science Act in the US (White House, 2022), which aims to boost American semiconductor research, development, and production.

1.6 Outside Assistance

There are no reports of outside assistance at the time of writing this report.

1.7 “Did you feel it?” Reports

Did You Feel It? (DYFI) is a system developed by the USGS to make use of reports provided by people who felt the earthquake. By taking advantage of the vast number of Internet users, it is possible to get a more complete description of what people experienced during the earthquake, the effects of an earthquake, and an empirical estimate of the spatial distribution of intensities (USGS, 2022a).

The DYFI Map and related products produced by the USGS are created within minutes of each earthquake of magnitude 1.9 or greater. The origin information (location and time) of each earthquake is provided by the Advanced National Seismic System (ANSS) and its regional and national network partners in the U.S.

At the moment of writing this report, for this event, the DYFI survey available at the USGS website had about 156 responses within the first 24 hours after the earthquake. The evolution over time of these responses is shown in Figure 1.2. It is worth noting that only a few people know about USGS’s DYFI in Taiwan.

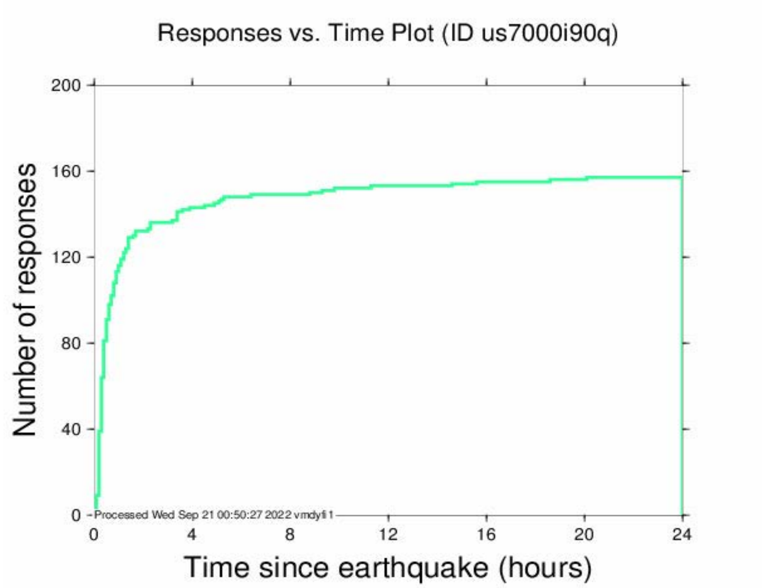


Figure 1.2. “Did you feel it?” (DYFI) responses collected by the USGS (USGS, 2022a).

From DYFI responses shown in the maps of Figure 1.3, it can be observed that most of the reported intensities fall within levels IV, V, and VI along the western coast of the country, and a few level IX intensities were reported close to the epicenter. The attenuation of intensity with increasing hypocentral distance is presented in Figure 1.4.

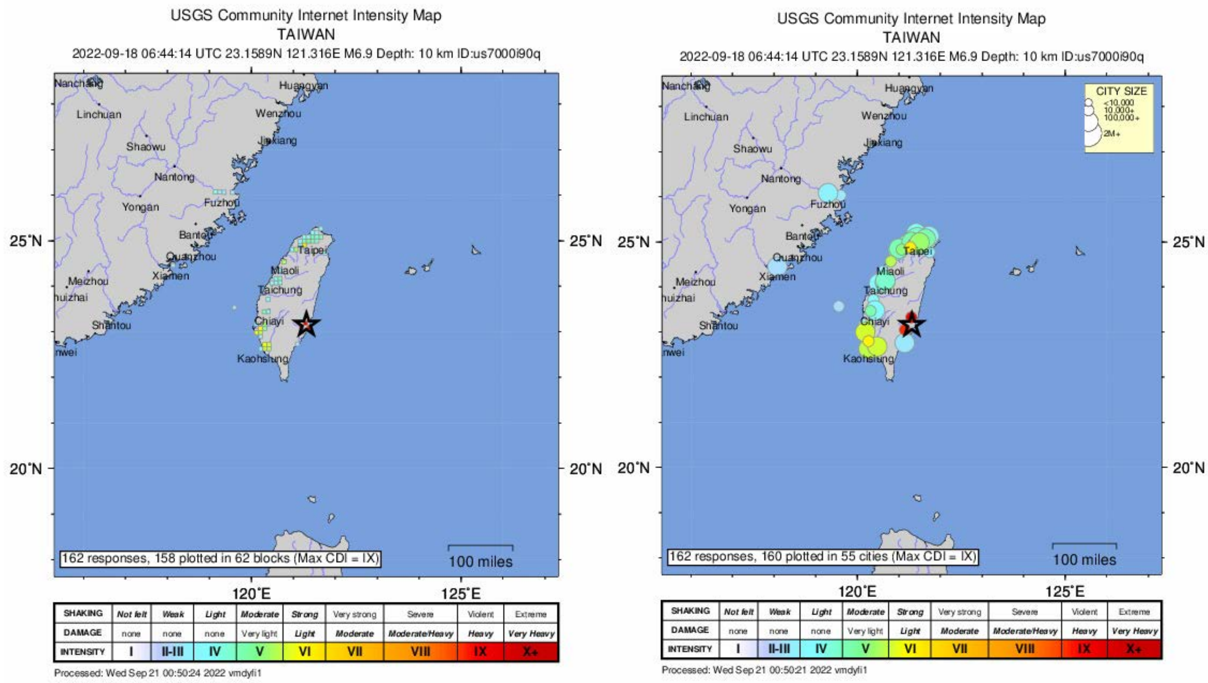


Figure 1.3. (a) Geocoded location and (b) City map of Modified Mercalli Intensity inferred from DYFI responses (USGS, 2022a).

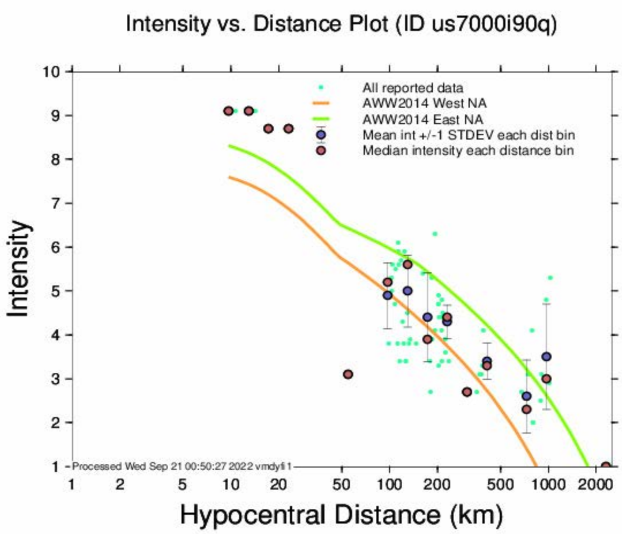


Figure 1.4. Attenuation of Modified Mercalli Intensity with increasing hypocentral distance compared with empirical relationships (USGS, 2022a).

1.8 Impacts

1.8.1 Population exposure estimate by USGS Pager

PAGER (Prompt Assessment of Global Earthquakes for Response), a product of the USGS, is an automated system that produces order-of-magnitude estimates of the impact of significant earthquakes around the world, informing emergency responders, government and aid agencies, and the media of the scope of the potential disaster. PAGER rapidly assesses earthquake impacts by comparing the population exposed to each level of shaking intensity with models of economic and fatality losses based on past earthquakes in each country or region of the world. USGS utilized PAGER to estimate earthquake impacts rapidly after the event. For example, PAGER can quickly produce rough estimates of earthquake casualties and economic losses to inform emergency responders, governments, and international aid agencies.

Figure 1.5 shows the isoseismals estimated for the M_w 6.9 earthquake based on the Modified Mercalli Intensity (MMI) scale and the population exposed to the various levels of shaking intensities. Figure 1.5 shows that approximately 138,000 people were exposed to the highest levels of shaking intensities (MMI VII and VIII combined), while 300,000 people were exposed to a MMI VI (strong intensity). Combined, the total population exposed to strong, very strong, or severe intensities was 438,000. To examine the breakdown of MMI felt in different cities throughout Taiwan, Figure 1.6 shows the number of people exposed to different ground shaking intensities (MMI) in selected cities as a result of the earthquake. Based on these populations, the total population of cities that experienced MMI of VI (strong) or higher is 215,000.

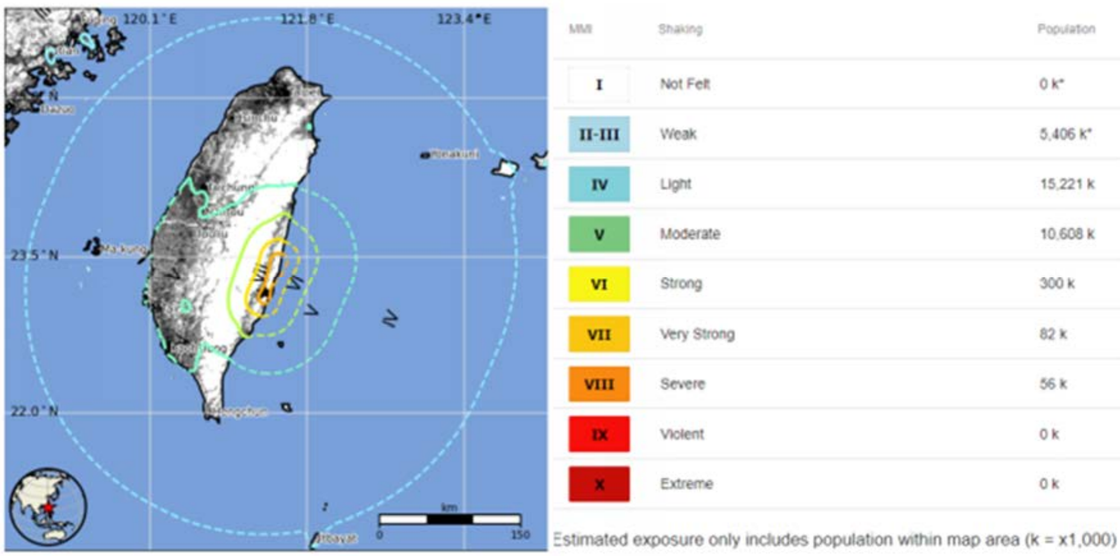


Figure 1.5. Isoseismals (curves of equal MMI) estimated for the M_w 6.9 earthquake (USGS, 2022a).

Selected City Exposure
from GeoNames.org

MMI	City	Population
VI	Taitung	<1k
VI	Taitung City	110k
VI	**Douliu**	**105k**
V	Hualien City	350k
V	Pizitou	5k
V	Jiayi Shi	<1k
V	**Tainan**	**771k**
V	**Taipei**	**7,872k**
V	**Kaohsiung**	**1,520k**
IV	**Taichung**	**1,041k**
IV	Zhongxing New Village	26k

bold cities appear on map. (k = x1000)

Figure 1.6. Number of people exposed to different ground shaking intensities (MMI) in selected cities as a result of the earthquake (USGS, 2022a).

1.8.2 Estimated Loss of Life and Injures

PAGER uses Shake Maps as input to estimate potential fatalities according to historical data of the region. For this earthquake, PAGER quickly estimated a probability distribution of fatalities and economic losses in U.S. dollars (Fig 1.7a). The number of shaking-related fatalities was expected to be less than 10 with ~75% probability. At the time of writing this report, 1 fatality and 171 injuries have been reported (Lai & Moritsugu, 2022; 中央通訊社, 2022). PAGER also estimated economic losses due to damage to be between $0 and $1 million, between $1 million and $10 million, between $10 million and $100 million, and between $100 million and $1,000 million with probabilities of 11%, 27%, 35%, and 20%, respectively (Fig 1.7b).

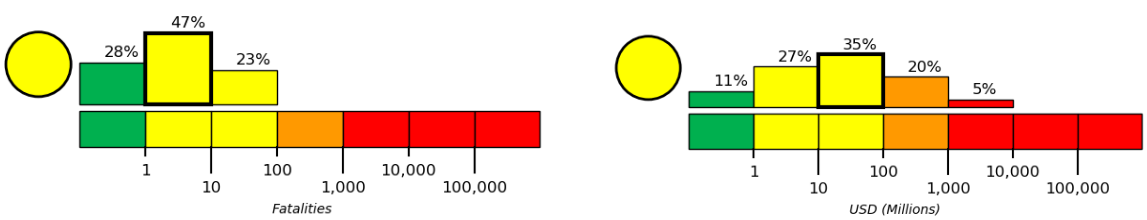


Figure 1.7. PAGER Estimated probability of (a) fatalities and (b) economic losses due to the earthquake (USGS, 2022a).

2.0 Seismological Aspects

2.1 Tectonics of the Region

Taiwan is located in a region that is characterized by a complex tectonic arrangement comprising two subduction zones of reverse polarities where it lies near the convergent boundaries of three major tectonic plates - the Eurasia plate to the north and west, the Philippine Sea plate to the east and southeast, and the Sunda plate to the southwest, as shown in Figures 2.1 and 2.2 (Caltech

Tectonics Observatory, 2005; USGS, 2022a; USGS, 2022c). Off Taiwan's northeast coast, the northwestern margin of the Philippine Sea plate is subducting underneath the Eurasian Plate along the Ryukyu trench which is clearly marked by high seismicity along a north-dipping seismic zone extending down to about 300 km, and where the majority of seismic energy release near Taiwan originates (Shing and Teng, 2001; Sun et al., 2015). Around Taiwan's southern tip and off its southwestern coast, the Eurasia plate is subducting eastward under the Philippine Sea plate, which outlines a region of east-dipping seismic zone extending down to about 200 km (Shing and Teng, 2001). The modern suture zone is located along the Longitudinal Valley along Taiwan's east coast and is characterized by occasional large shallow strike-slip earthquakes, where in the geological past, this suture zone might have behaved more thrustlike (Shin & Teng, 2001). In the region extending between these two subduction zones and in the midsection of western Taiwan, there are a series of large thrust fronts which take up the bulk of the plate convergence rate (Shin & Teng, 2001). As a result, the interaction of these two plates gives rise to a very complex tectonic structure.

As a young orogenic belt, Taiwan experiences very active tectonic motion, where the plate boundary is distinguished by a zone of arc-continent collision such that the northern end of the Luzon island arc in the Philippines, is colliding with the buoyant crust of the Eurasia continental margin located offshore China, which resulted in the Taiwanese mountain range ~ 6.5 M years ago (Caltech Tectonics Observatory, 2005; Lin et al., 2003; Smoczyk et al., 2013; Sun et al., 2015; USGS, 2022a; USGS 2022c). This collision zone transitions into the eastward-oriented Manila subduction zone along Taiwan's west coast, and extends south (USGS 2022a; USGS 2022c). The high seismic activity in this region is attributed to the rapid northwest convergence of the Philippine Sea plate toward the Eurasia plate. The Philippine Sea plate moves towards the Chinese mainland margin at around 82 mm/yr, which is considered to be one of the highest convergence rates in the world and has an azimuth of 306° (Shin & Teng, 2001; Sun et al., 2015). Across the Longitudinal Valley Fault, the velocity jumps by 30 mm/yr, which is the suture zone of active plate collision in Taiwan as demonstrated above (Sun et al., 2015). Additionally, rotations at both tips of the Taiwan collision belt (clockwise in northeast Taiwan and anticlockwise in southwest Taiwan) are observed, which can be related to the escape tectonics of Taiwan (Sun et al., 2015).

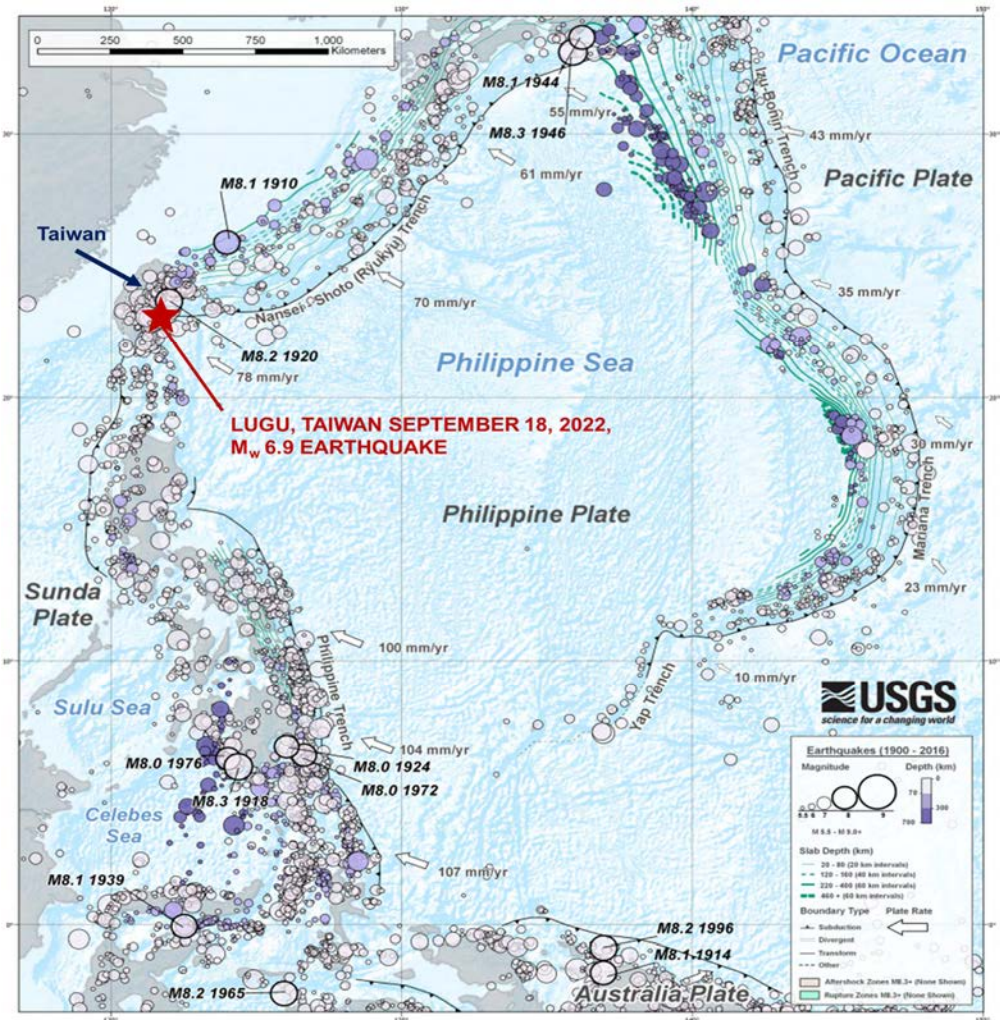


Figure 2.1. Seismotectonic features of the extended Taiwan region (adapted from USGS, 2022c).

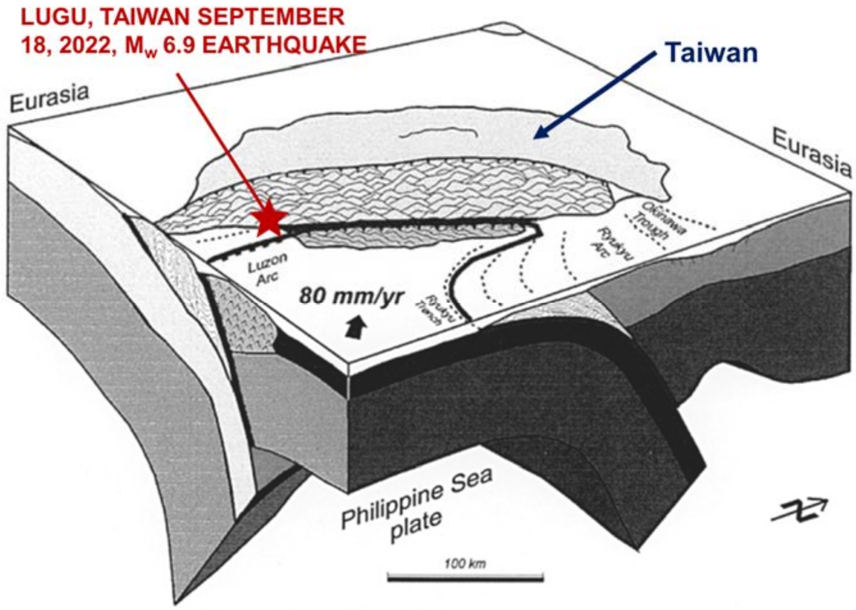


Figure 2.2. Three-dimensional schematic diagram of Taiwan's plate tectonics (adapted from Shin & Teng, 2001).

Such a high plate convergence rate has resulted in many large faults across Taiwan. There are a series of approximately north-south-trending and east-dipping large thrust faults in the midsection of western Taiwan that have generated occasional large, and consequently, damaging earthquakes. Taiwan's seismic energy release per unit area, is conceivably five times higher than that of California (Shin and Teng, 2001). In Taiwan, many of the earthquakes are related to the subduction zones in the offshore area, either to the northeast or to the southeast, and have only minor impacts on society due to their larger focal depth and hypocentral distance. However, with the development of large population centers over the western coastal plain of Taiwan, occasional large and shallow earthquakes that occur along some of the large thrust faults in the western foothills and over the Holocene plains further to the west can sometimes cause catastrophes (Shin and Teng, 2001). One example is the relatively recent 1999 M_w 7.7 Chi-Chi earthquake which had a very energetic aftershock sequence, similar to many large Taiwan earthquakes in the past, with 87 M > 5 aftershock events, which including 13 events with M > 6, and 7 events with magnitudes larger than or equal to the 1994 M_w 6.7 Northridge mainshock. Even one year after the mainshock, another M 6.7 aftershock caused considerable damage in the areas near the southern end of the Chelungpu fault (Shin and Teng, 2001).

The September 18, 2022, M_w 6.9 earthquake south-east of Lugu, Taiwan, occurred due to strike-slip faulting at a shallow depth, located near the plate boundary between the Philippine Sea and Eurasia plates on the southeast coast of Taiwan (USGS, 2022a). The preliminary solutions for the earthquake's focal mechanism show that the rupture occurred on a steep fault striking either east-southeast (right-lateral) or south-southwest (left-lateral) (USGS, 2022a). The Eurasia plate converges with the Philippine Sea plate at a rate of approximately 73 mm/yr towards the northwest at the location of this earthquake (USGS, 2022a). The location, depth, and focal mechanism of the September 18, 2022 earthquake are consistent with its occurrence along a fault near the complex plate boundary in this region, where an earthquake of similar size and mechanism generally has a rupture of about 50 km long and 15 km wide (USGS, 2022a).

2.2 Seismicity of the Region

Because of its plate boundary location, Taiwan is a highly active seismic region and commonly experiences moderate-to-large earthquakes. Figure 2.3 presents the location of earthquakes within the region between 1898 and 1997, which closely follows the tectonic setting presented in Figure 2.2. Figure 2.4 maps the epicenters of the events with M_w greater than or equal to 6.0 and 7.0 since 1900 within the region, whereas Figure 2.5 depicts the distribution of earthquake epicenters with $M_w \geq 3.0$ from 1975 to 2014. The region within 250 km of this September 18, 2022 earthquake has hosted 239 other $M_w \geq 6.0$ earthquakes over the preceding century; 24 of these earthquakes had $M_w \geq 7.0$ (USGS, 2022a).

The region has experienced several major earthquakes in the last century, such as the 1906 M_w 7.1 Meishan earthquake, 1935 M_w 7.1 Hsinchu-Taichung earthquake, and 1999 M_w 7.6 Chi-Chi earthquake. The latter and largest inland earthquake of the twentieth century in Taiwan, known as 'The great earthquake of September', took place on September 21, 1999, in Central Taiwan near the town of Chi-Chi. The epicenter had a focal depth of 8 km for a north-south trending and east-dipping thrust faulting mechanism that ruptured a segment of approximately 100 km of the Chelengpu thrust fault. The epicenter of this event is shown in Figure 2.5 by the largest circle labeled '1999'. The densely populated central region of Taiwan was severely affected by the earthquake resulting in 2,470 fatalities, 11,305 injured, and over 100,000 structures destroyed amounting to a total of US$10 billion worth of damage (Shin and Teng, 2001).

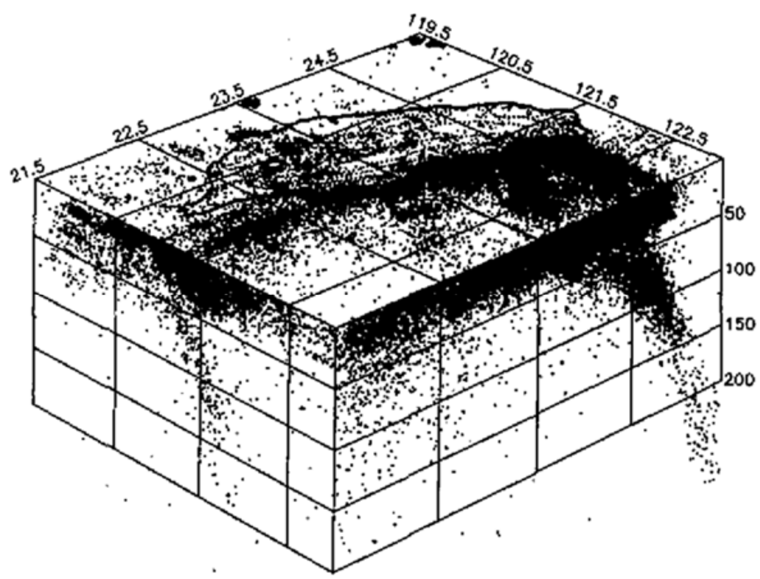


Figure 2.3. Location of earthquakes recorded in Taiwan over a 100-year period (1898-1997). Note the relationship with the tectonic setting of the region (Figure 2.2). (Wang & Shin, 1998).

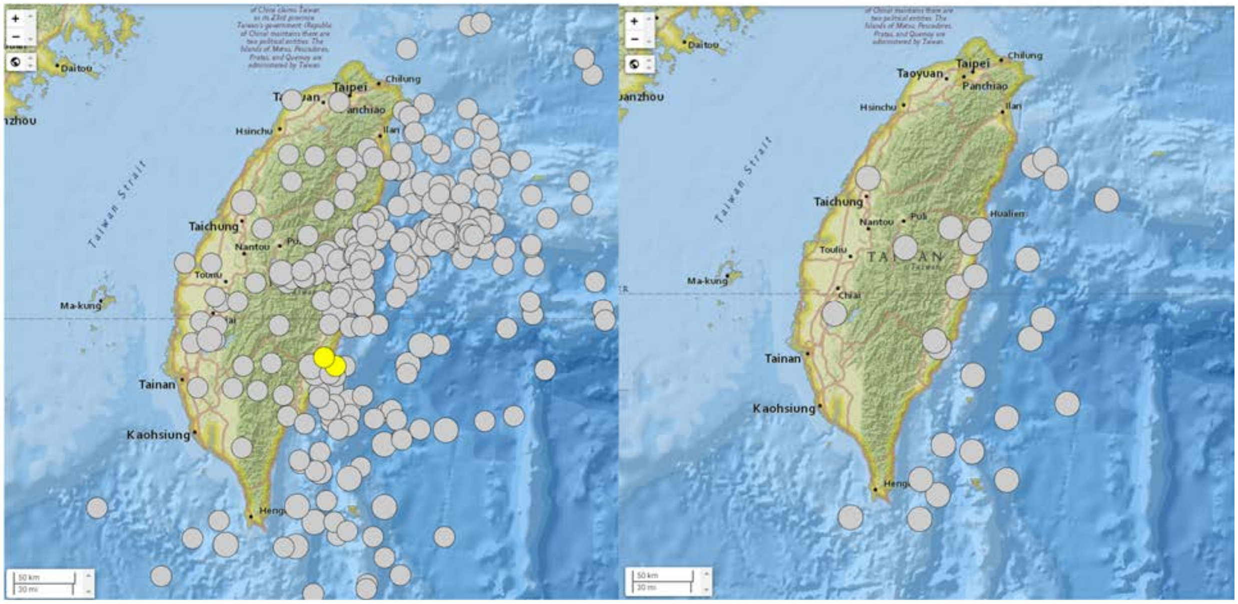


Figure 2.4. Map of the epicenters of earthquakes with (a) $M_w \geq 6.0$; and (b) $M_w \geq 7.0$, in Taiwan since 1900. Source: USGS ComCat. (USGS, 2022b).

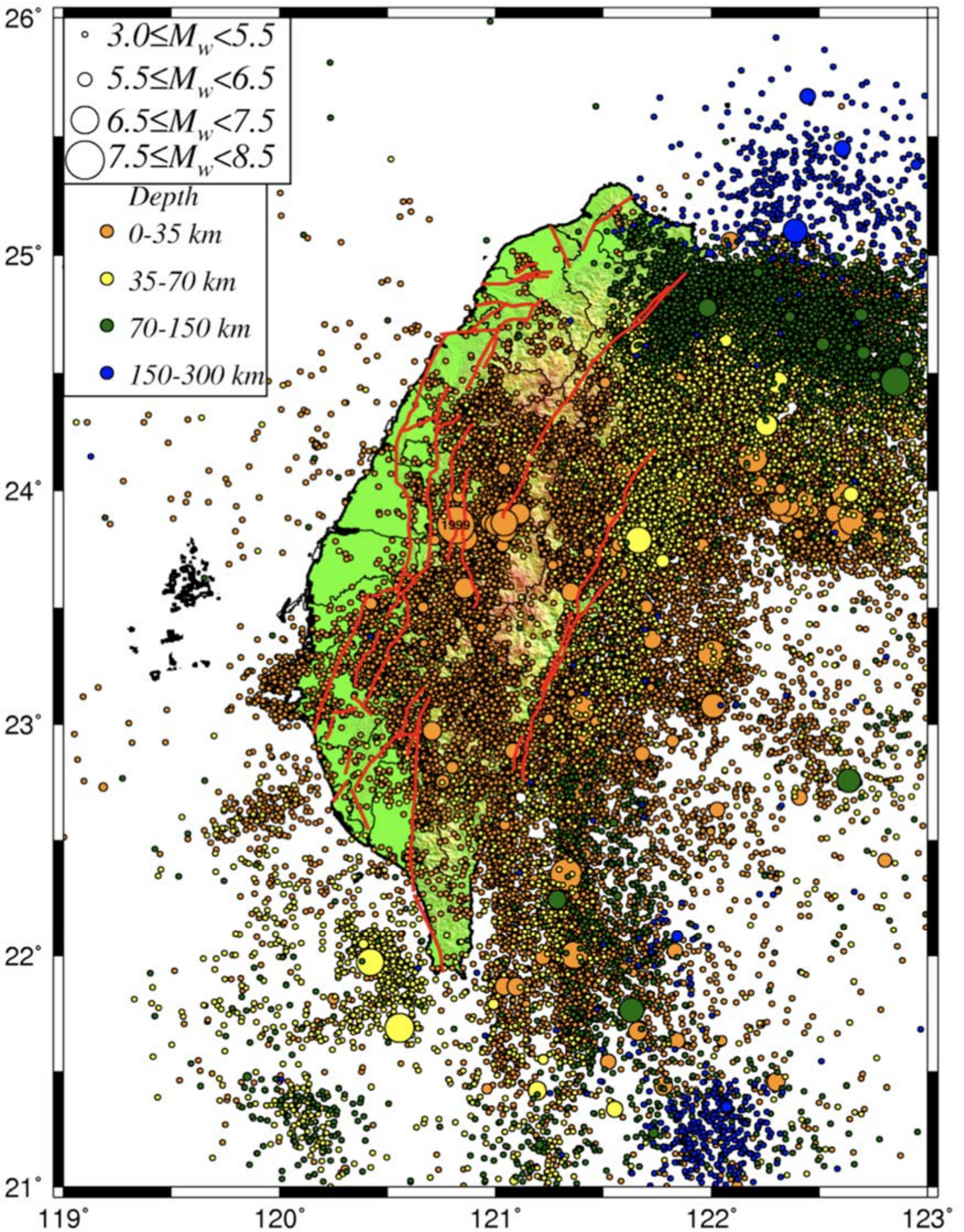


Figure 2.5. Map of the epicenter distribution of earthquakes in Taiwan with $M_w \geq 3.0$ from 1975 to 2014. (Chang et al., 2017).

2.3 The September 18, 2022 M_w6.9 Earthquake

On September 18, 2022, at approximately 2:44 pm local time (06:44:14 UTC), a moment magnitude M_w 6.9 (M_L = 6.8, according to the Central Weather Bureau Seismological Center 2022) earthquake struck 42.7 km north of Taitung City, 87.1 km southeast of Lugu, 96.5 km southwest of Hualien City and 87.5 km east of Yujing, as shown in Figure 2.6. The USGS located the hypocenter at 23.159°N 121.316°E, with a depth of 10 km (USGS, 2022a), whereas the Central Weather Bureau Seismological Center located the hypocenter at 23.14°N 121.20°E, with a depth of 7 km (Central Weather Bureau Seismological Center, 2022).

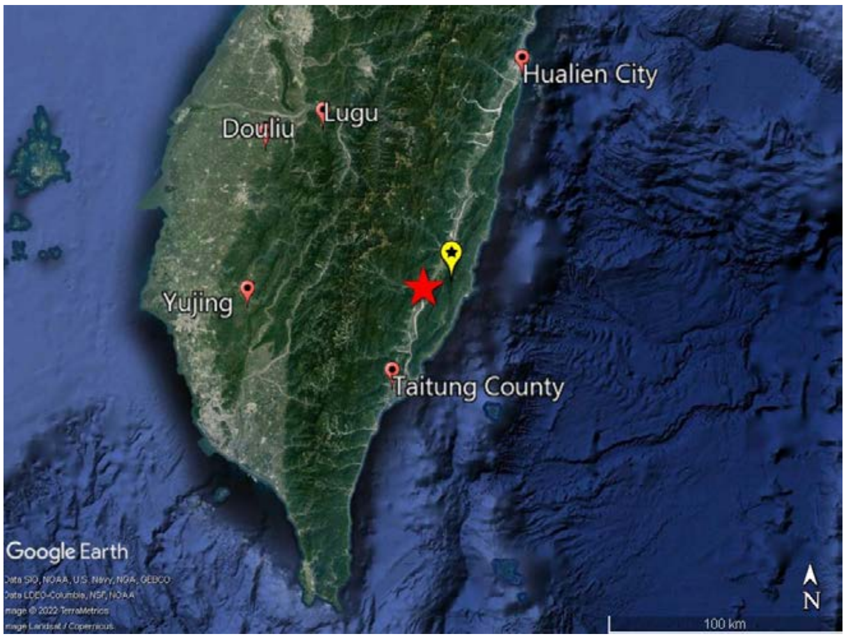


Figure 2.6. Epicenter of the September 18, 2022, earthquake. The red star represents the epicenter located by the Central Weather Bureau Seismological Center (Central Weather Bureau Seismological Center, 2022), whereas the yellow marker represents the epicenter located by USGS (USGS, 2022a).

The September 18, 2022, mainshock was preceded by a foreshock sequence of multiple minor earthquakes. According to the information provided by the Central Weather Bureau Seismological Center (Central Weather Bureau Seismological Center, 2022), approximately seventy earthquakes with magnitudes higher than M_L = 3 and five earthquakes with magnitudes higher than M_L = 5 preceded the main event. The foreshock sequence began on September 17, 2022, at 9:41 pm local time (13:41:17 UTC) with a M_w = 6.5 event (M_L = 6.4) and culminated on September 18, 2022, at 2:33 pm local time (06:33:25 UTC) with a M_L = 4 event (Central Weather Bureau Seismological Center 2022). As of September 20, 2022, more than 90 aftershocks with M_L > 3 have been identified after the main event (Central Weather Bureau Seismological Center 2022). Figure 2.7 shows the epicenters of the foreshocks and aftershocks of the September 18 earthquake using data obtained from the Central Weather Bureau Seismological Center (Central Weather Bureau Seismological Center, 2022).

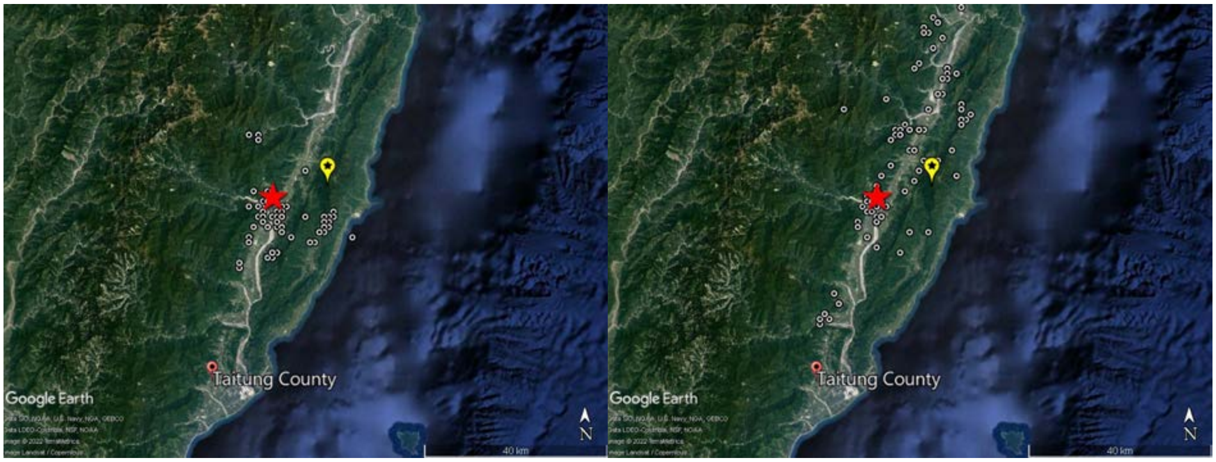


Figure 2.7. Epicenters of foreshocks (left) and aftershocks (right) of September 18, 2022, earthquake (black and white dots). The red star represents the epicenter located by the Central Weather Bureau Seismological Center (Central Weather Bureau Seismological Center, 2022), whereas the yellow marker represents the epicenter located by USGS (USGS, 2022a).

The W-phase Moment Tensor inversion solution of the earthquake, as reported by the USGS (USGS, 2022a), indicates a strike-slip focal mechanism (Figure 2.8). As shown in Table 2.1, one nodal plane corresponds to left-lateral movement on a fault striking in the NE-SW direction, and the other indicates right-lateral movement on a fault striking SE-NW. Both nodal planes present a slight thrust component and a steep dipping. The causative plane is more likely defined by Fault Plane 1, striking in the SE-NW direction. For this solution, the cross section and the surface projection of the slip distribution are shown in Figure 2.9 (USGS, 2022a). This fault plane is also consistent with measurements of co-seismic offset tracking using Sentinel-2 satellite imagery of the European Commission's Copernicus program (Figure 2.10).

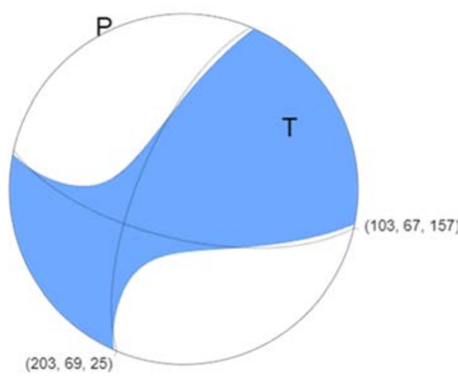


Figure 2.8. Fault plane solutions from USGS (USGS, 2022a). Moment Tensor solution for the September 18, 2022 earthquake, according to USGS (USGS, 2022a).

Table 2.1. Fault plane solutions from USGS (USGS, 2022a). The causative plane is more likely to correspond to the Fault Plane 1 solution.

Fault Plane 1			Fault Plane 2		
Strike	Dip	Rake	Strike	Dip	Rake
203	69	25	103	67	157

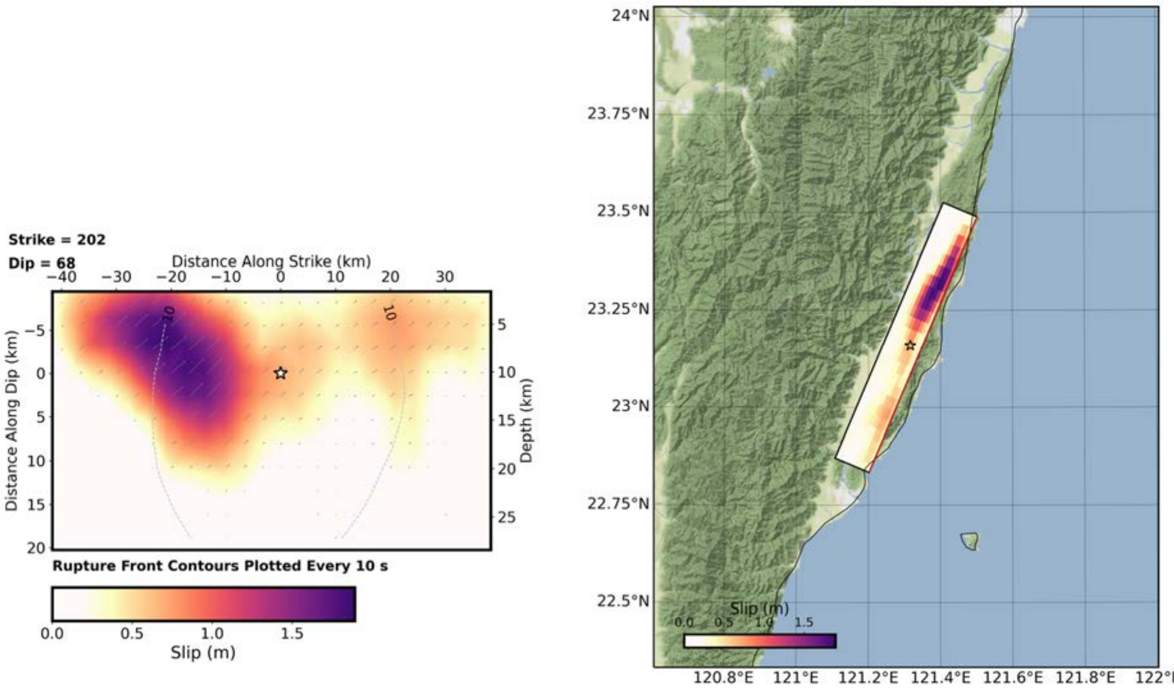


Figure 2.9. Cross section and surface projection of the slip distribution (USGS, 2022a).

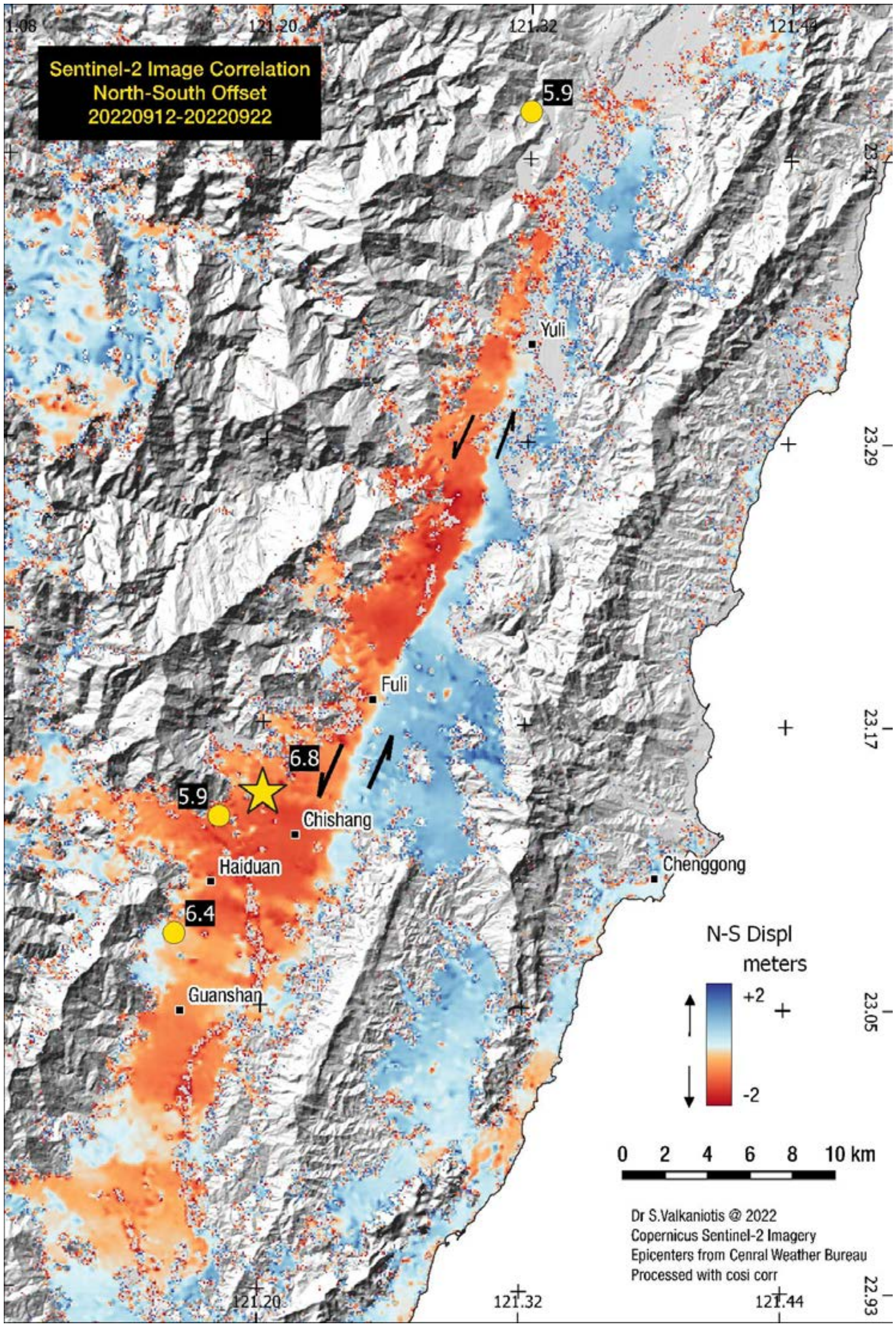


Figure 2.10. North-South co-seismic offset tracking using Sentinel-2 satellite imagery. The yellow star represents the epicenter of the mainshock earthquake, whereas the yellow circles represent the largest foreshocks and aftershocks (Valkaniotis, 2022).

2.4 Ground Motion Intensities

The USGS ShakeMap estimated a MMI of VIII and a Peak Ground Acceleration (PGA) of approximately 0.4 g in the epicentral region, as shown in Figure 2.11 (USGS, 2022a). Similarly, the Central Weather Bureau Seismological Center (Central Weather Bureau Seismological Center, 2022) of Taiwan estimated a maximum intensity (Central Weather Bureau seismic intensity scale) of 6+, corresponding to “very strong” shaking, as illustrated in Figure 2.12. Figure 2.13 presents maps of peak ground acceleration (PGA) and peak ground velocity (PGV) within Taiwan (Central Weather Bureau Seismological Center, 2022).

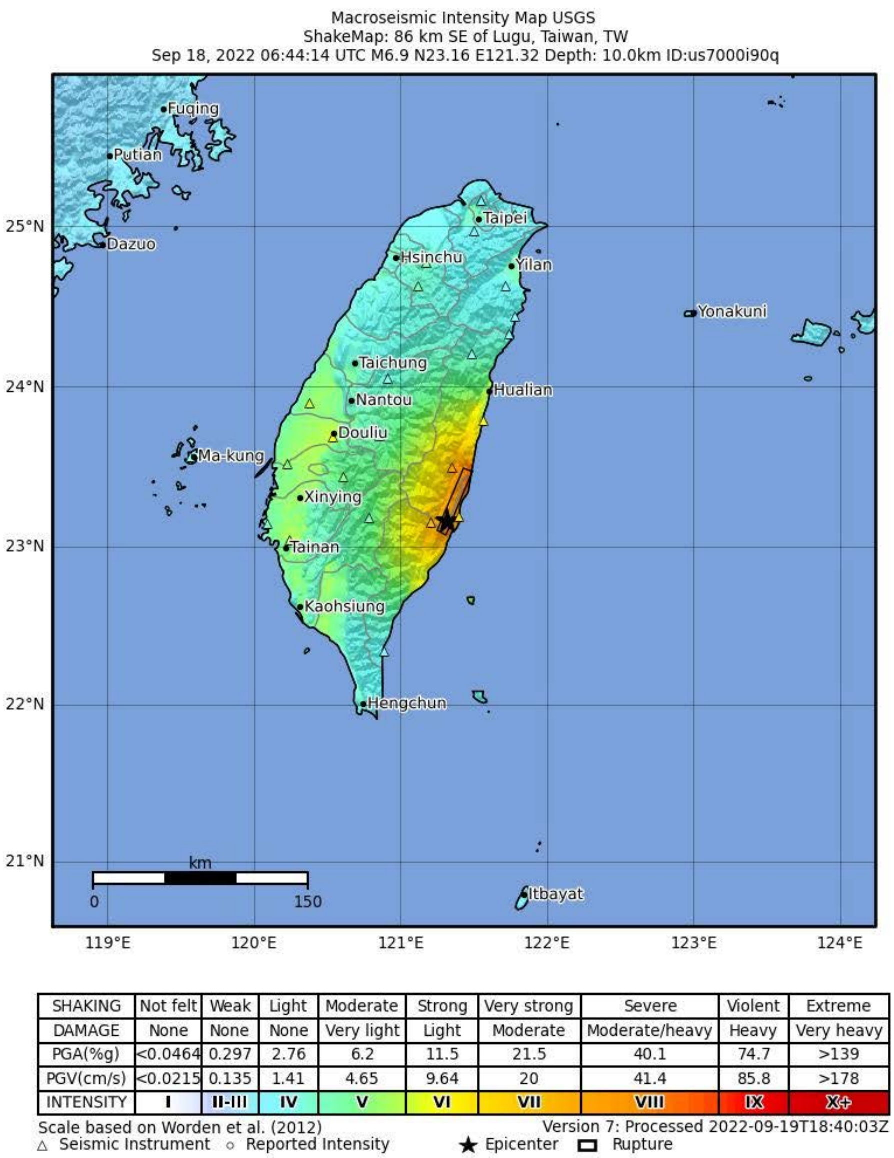


Figure 2.11. Intensity map estimated from ShakeMap (USGS, 2022a).

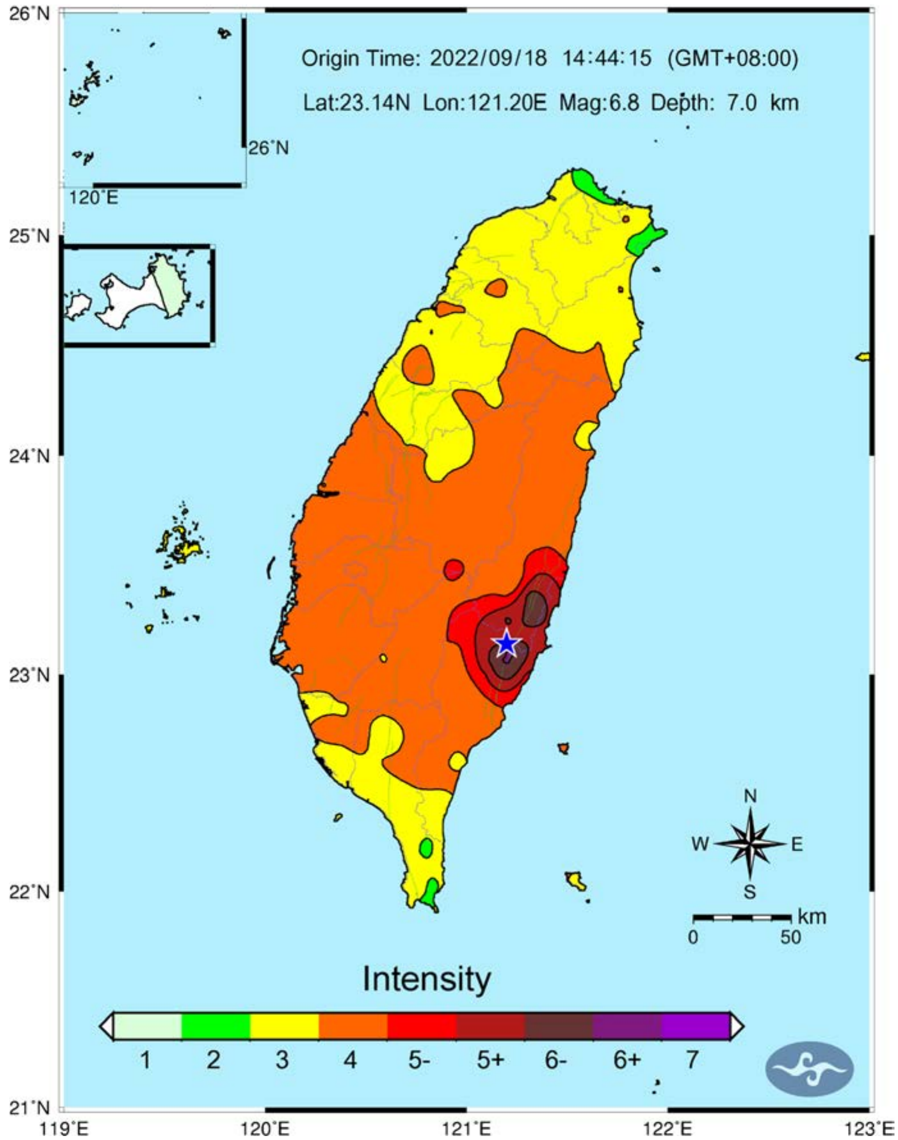


Figure 2.12. Central Weather Bureau seismic intensity map estimated by the Central Weather Bureau Seismological Center (Central Weather Bureau Seismological Center, 2022).

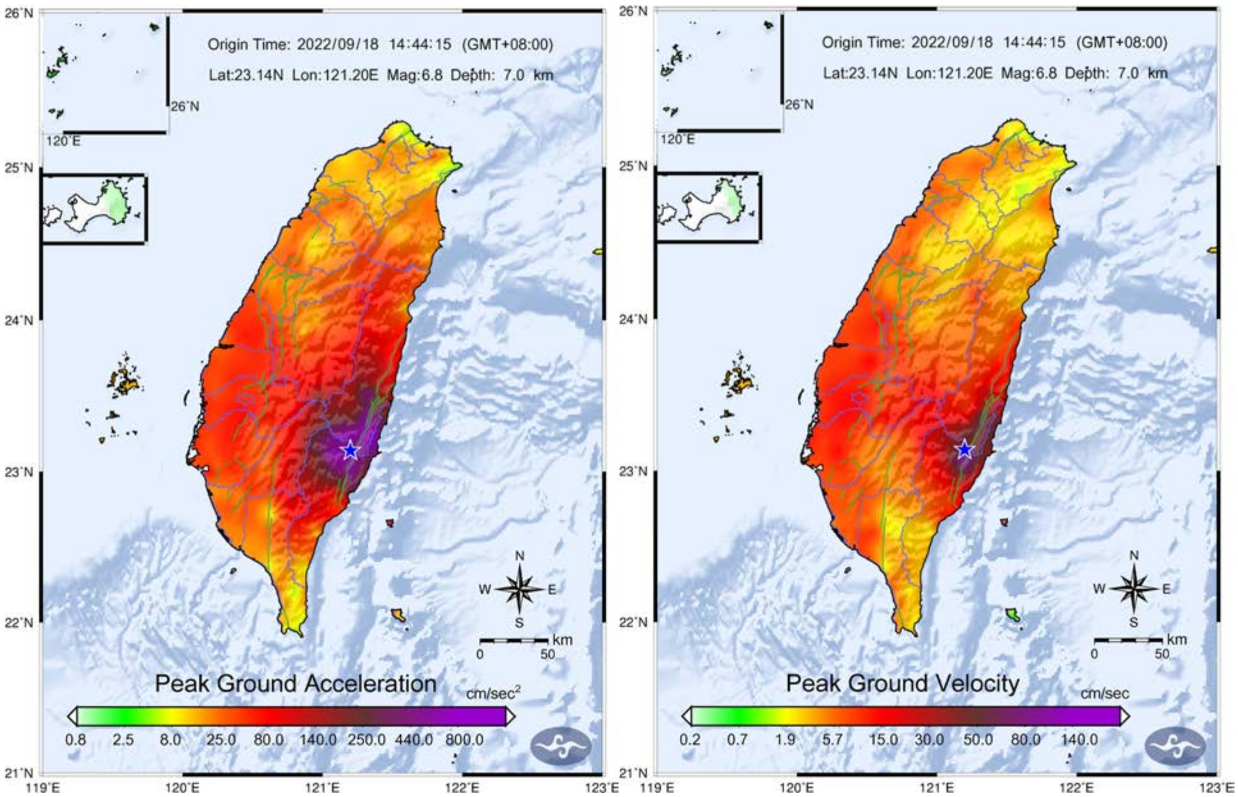


Figure 2.13. Map of (a) PGA; and (b) PGV in Taiwan estimated by the Central Weather Bureau Seismological Center (Central Weather Bureau Seismological Center, 2022).

At the time of this writing, the Central Weather Bureau Seismological Center (Central Weather Bureau Seismological Center, 2022) had published PGA and PGV of 125 strong-motion stations that recorded the event in Taiwan. Table 2.2 lists the PGA and PGV recorded by the 13 stations closest to the earthquake epicenter, all within a distance of 50 km. Detailed information about the rest of the stations can be found on the event website provided by the Central Weather Bureau Seismological Center (Central Weather Bureau Seismological Center, 2022). As can be seen in Table 2.2, the largest instrumental PGA was 0.51 g, which was recorded in the north-south direction at Yuli station (EYUL), whereas the largest instrumental PGV was 97.14 cm/s, recorded in the east-west direction at Chishang station (ECS).

Table 2.2. List of the 13 stations closest to the earthquake epicenter (Central Weather Bureau Seismological Center, 2022).

Station Code	Station Name	Station Lon [°]	Station Lat [°]	Distance [km]	PGA [g]			PGV [cm/s]		
					NS	EW	Geomean	NS	EW	Geomean
EHD	Haiduan	121.21	23.15	1.28	0.31	0.22	0.26	28.1	27.6	27.8
ECS	Chishang	121.22	23.10	4.94	0.43	0.43	0.43	90.2	97.1	93.6
FULB	Fuli	121.29	23.20	11.46	0.46	0.42	0.44	44.8	30.5	37.0
CHK	Chenggong	121.37	23.10	17.91	0.18	0.26	0.22	22.8	34.1	27.9
EDH	Donghe	121.30	22.97	20.97	0.09	0.11	0.10	15.8	10.9	13.1
EYUL	Yuli	121.32	23.35	26.06	0.51	0.43	0.47	54.3	52.7	53.5
LONT	Luye	121.13	22.91	26.68	0.11	0.20	0.15	11.1	21.0	15.2
ECB	Changbin	121.45	23.32	32.17	0.26	0.22	0.24	32.8	25.5	28.9
TWG	Beinan	121.08	22.82	37.61	0.03	0.03	0.03	4.5	7.1	5.6
EHY	Hongye	121.33	23.50	42.58	0.41	0.33	0.37	16.5	24.5	20.1
TTN	Taitung City	121.15	22.75	42.94	0.04	0.06	0.05	10.5	15.4	12.7
STYH	Taoyuan	120.78	23.18	43.50	0.05	0.05	0.05	3.3	4.0	3.6

Free-field ground motions recorded by the Taiwan Strong Motion Instrumentation Program network (TSMIP) were obtained from the Taiwan Geophysical Database Management System (CWB, 2022). The ground motion accelerograms were first filtered and instrument corrected, resulting in 341 stations with usable recordings. The corrected accelerograms were then used to compute RotD50 values (Boore, 2010) of two ground motion intensity measures: PGA and spectral acceleration at a period of 1s, Sa(1s). Figure 2.14 shows a map with the distribution of the computed PGA and Sa(1s) values.

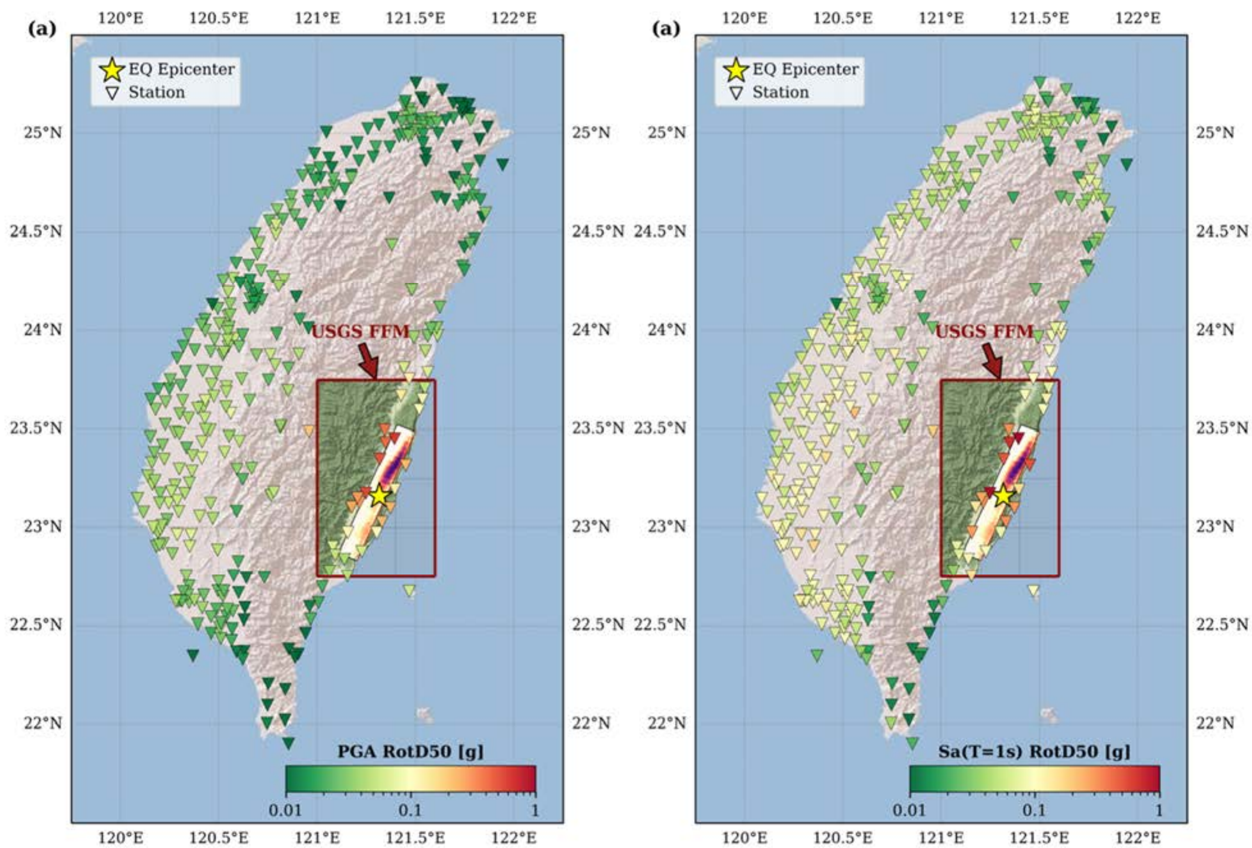


Figure 2.14. Map of RotD50 values of (a) PGA and (b) Sa(1s) recorded by the 341 strong-motion stations of the TSMIP network. The finite fault model (FFM) estimated by the USGS is also shown for reference.

The computed intensity measures were also compared with the ground motion model (GMM) developed by Boore et al. (2014). The comparisons for PGA and Sa(1s) are shown in Figure 2.15 and Figure 2.16, respectively. The left panels of these figures show the intensity values as a function of Joyner-Boore distance, which were computed using the finite fault provided by USGS (2022a), and are compared to predictions of the GMM for reference sites with time-averaged shear wave velocity over the upper 30 meters of the earth's surface (V_{S30}) of 200 m/s and 500 m/s. The depth to the shear-wave velocity horizon of 1 km/s (z_1) was assumed to be unknown for these reference sites. The right panels of Figures 2.15 and 2.16 show the normalized residuals of all stations for PGA and Sa(1s), respectively. The residuals were computed using V_{S30} and z_1 values obtained from the Engineering Geological Database for TSMIP (NCREE, 2022a). For stations not included in this geological data, V_{S30} values were obtained from a recently developed global database and z_1 values were assumed to be unknown when using the Boore et al. GMM (Heath et al., 2020; Boore et al., 2014). Although the intensities of most stations fall within ±1 standard deviation of the median, on average, the GMM tends to slightly overpredict PGA and underpredict Sa(1s).

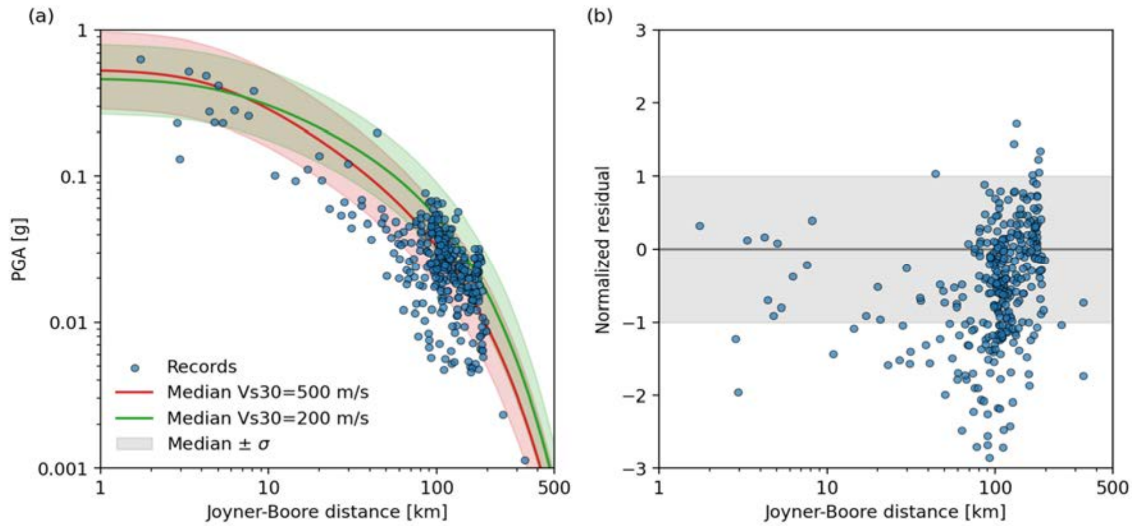


Figure 2.15. Comparison of recorded PGA values to those predicted by the Boore et al. (2014) ground motion model: (a) attenuation for reference sites of 200 and 500 m/s; (b) normalized residuals as a function of distance.

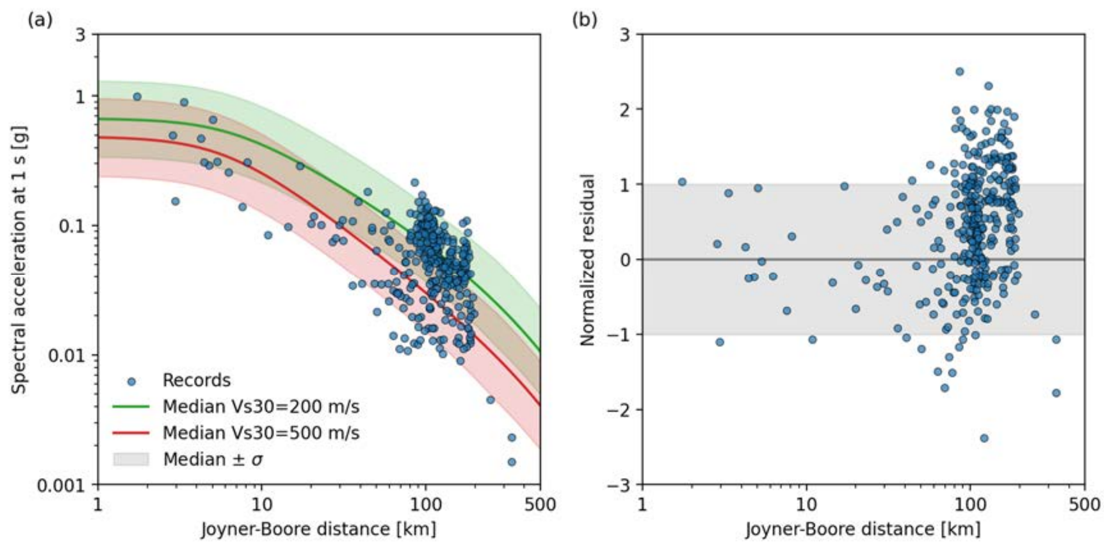


Figure 2.16. Comparison of recorded Sa(1s) values to those predicted by the Boore et al. (2014) ground motion model: (a) attenuation for reference sites of 200 and 500 m/s; (b) normalized residuals as a function of distance.

2.5 Early Earthquake Warning (EEW)

Taiwan has several Early Earthquake Warning (EEW) systems in place that broadcast warnings via a system of texts, TV, and public broadcast systems (Wu et al., 2021). The Central Weather

Bureau (CWB) EEW system is for the entirety of Taiwan. During recent earthquakes, the EEW system provided a 2 - 8 seconds warning around the epicenter. The National Taiwan University (NTU) system is a hybrid (regional and onsite) system based on Micro-Electro-Mechanical System (MEMS) sensors. The NTU system has Twitter (https://twitter.com/eew_p) and Facebook (https://www.facebook.com/Palert.Shakemap) accounts. Both CWB and NTU systems are able to produce EEW warnings within 20 seconds of an earthquake occurrence. The threshold for a regional warning to be broadcast is that the earthquake is to be above magnitude 4 or scale 5 (Earthquake Report-Central Meteorological Administration, 2022). The National Center for Research on Earthquake Engineering (NCREE) also has an EEW system that serves as a conduit for the NTU and CWB system warnings and also has its own network of around 98 stations.

The CWB EEW system operates on an Earthworm-based system (eBEAR) that includes 511 accelerometers, 68 short-period instruments, and 9 cable-based ocean bottom seismometers. Epicenters are calculated via both Geiger's (GE) method and the effective epicenter (EE) method (Chen et al., 2019). The effective epicenter method was introduced to shorten reporting times for earthquakes in offshore and poor station coverage areas (Wu et al., 2021). The average processing time for EEW reports between April to December 2020 was 10.5 sec for inland earthquake events and 20.9 sec for offshore earthquake events.

The NTU EEW system is composed of MEMS sensors installed in various elementary schools on the ground floor or first-floor building walls throughout Taiwan, which are shown in Figure 2.17. They are P-Alert-based instruments that record three-component data at 100 samples per second with 16-bit resolution and a full dynamic range of ± 2 g (Wu et al., 2021; Hsieh et al., 2015). If the threshold (PGA ≥ 80 Gal or progressive displacement value, P_{dv} ≥ 0.35 cm) within a recommended three-second window is triggered for an earthquake warning, an on-site warning within the school is issued and the data is sent to the CWB to be processed further for a potential regional warning (Hsieh et al., 2015). The average lead time is 13.8 s with a standard deviation of 4.5 s for a sample size of seven earthquake events (Wu et al., 2021). From the data, ShakeMaps covering PGV, Sa, CWB intensity maps, and PGA are plotted and sent to national disaster relief agencies for rescue operation planning.

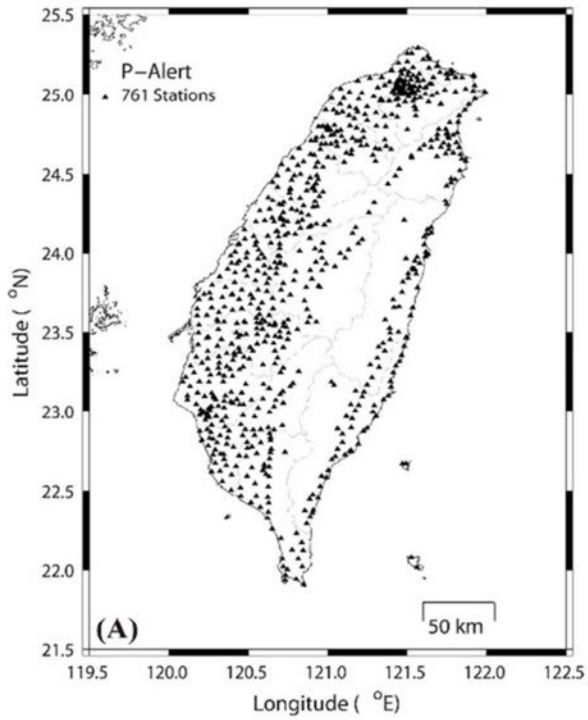


Figure 2.17. Distribution of NTU P-Alert MEMS sensors (Wu et al., 2021).

The NCREE EEW onsite system ties into alert broadcast systems at 3,514 schools across Taiwan to receive onsite alerts as well as CWB regional alerts. Whichever alert is received faster is broadcasted. The PGAs predicted by the NCREE stations are based on support vector machine algorithms with improved lead time performance with some stations recently upgraded to PGA prediction for every second of feature extraction (Hsu et al., 2013; Hsu et al., 2020). There is an overestimation for larger earthquakes and an underestimation for smaller earthquakes, but the predicted PGAs are within one scale of the true earthquake intensity (Wu et al., 2021).

3.0 Local Codes and Construction Practices

This section provides information on the existing building stock in Taiwan and the evolution of seismic codes in the past decades.

3.1 Existing Building Stock

According to 2020 statistics, the total housing stock in Taiwan is 8,900,427 units (Advanced Developers Association, 2020). There are 8.38% of units in detached houses, 68.87% of units in mid-rise structures with 2 to 5 floors, and 21.75% of units in high-rise structures. The average age of the housing stock is 30 years. In 2019, 116,079 housing units started construction (Advanced Developers Association, 2020) and received building permits two months prior to construction.

Soft stories are a common issue in many mid- to high-rise buildings in Taiwan constructed before the 1999 M_w 7.7 Chi-Chi earthquake (Yin, 2018; Naeim et al., 2000). Figure 3.1 shows a typical building with a soft story shored for stability following a previous earthquake.

Figure 3.1. Typical soft story building with masonry infill walls and temporary shoring (Naeim et al., 2000).

3.2 Building Codes

In 1974, Taiwan implemented a minimum seismic design force for buildings following the format of the US Uniform Building Code. In 1982, important factors for various building occupancy categories were further incorporated into the seismic design code (Chai et al., 2009). After the Mexico Earthquake in 1985, the basin effect of the Taipei Basin was recognized and a modified design spectrum for this region was developed. In 1997, major changes were adopted, including new dynamic analysis procedures using the response spectrum method, an increase in the number of seismic zones from 3 to 4, and a zoning factor that directly represents the design peak ground acceleration associated with a hazard level of 10% chance of exceedance in 50 years (Chai et al., 2009).

Taiwan has also revised its building codes after earthquakes that caused substantial damage. Particularly, after the 1999 M_w 7.7 Chi-Chi earthquake when it became a legal requirement for buildings and infrastructure to comply with standards such that buildings and infrastructure should be able to resist earthquakes of M_w 6.0 or greater. In addition, after the 1999 M_w 7.7 Chi-Chi earthquake, the significance of near-fault ground motions on buildings was acknowledged by the seismic code in Taiwan adding two "near-fault factors" to amplify the spectral value at longer periods (Chai, et al., 2009). The near-fault factors, which are functions of the distance from the fault, are determined by the characteristic earthquake model as well as the seismic hazard analysis for Taiwan (Chai & Teng, 2012). Figure 3.2 shows the shape of the design response spectrum developed by site-adjusted parameters S_{DS} and S_{D1} in Taiwan. More detailed information can be obtained from the seismic design code of Taiwan (CPA, 2011; Chai, et al., 2009).

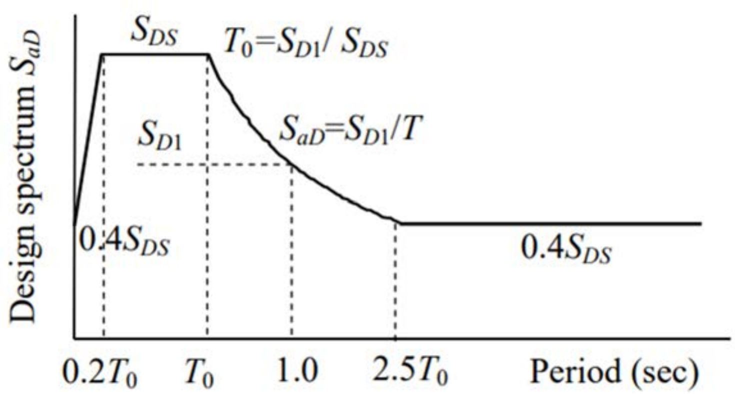
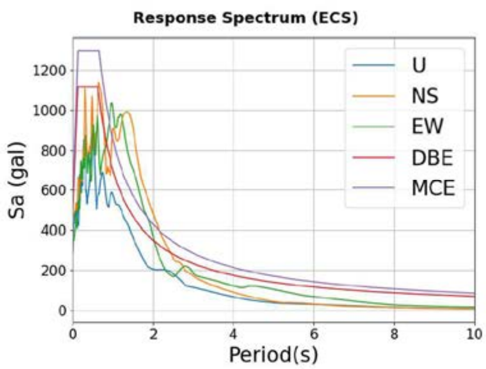
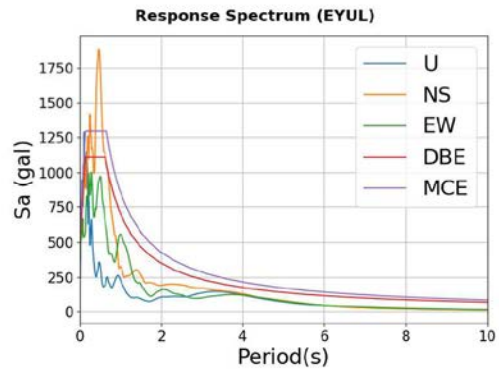


Figure 3.2. Design response spectrum in Taiwan (Chai & Teng, 2012).

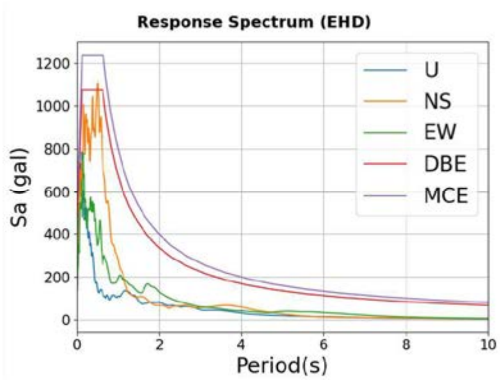
As compared to US codes (ASCE, 2016), in Taiwan, three seismic demand levels are considered: (1) Minimum Seismic Force (MSF), with an 80% probability of exceedance in 50 years; (2) Design Base Earthquake (DBE), with a 10% probability of exceedance in 50 years; and (3) Maximum Considered Earthquake (MCE), with a 2% probability of exceedance in 50 years. The MSF requirement is prescribed to avoid any nonlinear demand on structural elements during frequently occurring small earthquakes (Chai et al., 2019). For DBE level, the design response spectrum can be developed for general sites, near-fault sites, and the Taipei Basin (Chai & Teng, 2012). Figure 3.3 shows the comparison of response spectra computed from recorded horizontal (NS and EW) and vertical (U) accelerations at different stations during the September 18 earthquake to the elastic design spectrum for the DBE and MCE levels (NCREE, 2022b). It is noted that the response spectra are shown for a wide range of periods (i.e., up to 10 sec). Longer period structures can be tall buildings or long bridges, such as the collapsed 600 meter long Gaoliao bridge. From these response spectra, it can be observed that the response spectra of some of the recorded motions are close to and slightly above the design levels for short period structures and below the design level for longer period structures.


Response Spectrum (ECS)
Sa (gal)
Period(s)
U
NS
EW
DBE
MCE

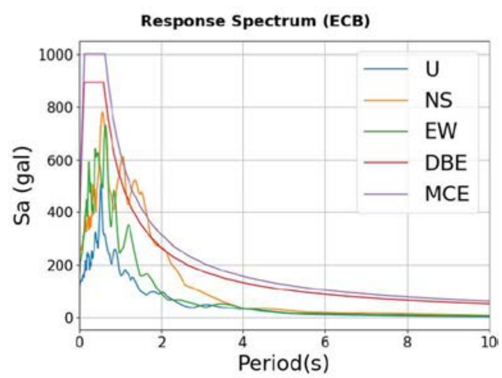
(a)


Response Spectrum (EYUL)
Sa (gal)
Period(s)
U
NS
EW
DBE
MCE

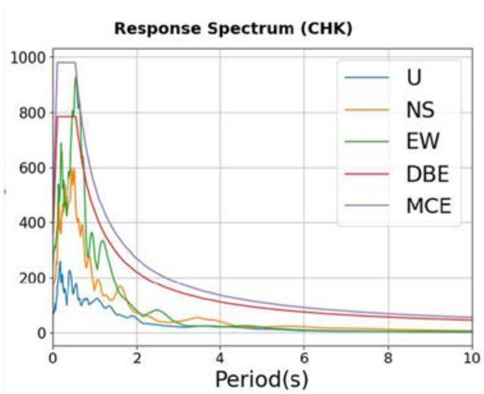
(b)


Response Spectrum (EHD)
Sa (gal)
Period(s)
U
NS
EW
DBE
MCE

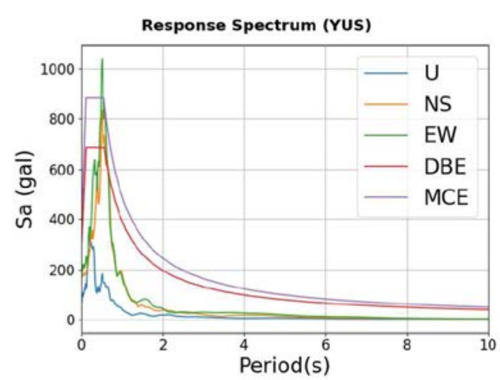
(c)


Response Spectrum (ECB)
Sa (gal)
Period(s)
U
NS
EW
DBE
MCE

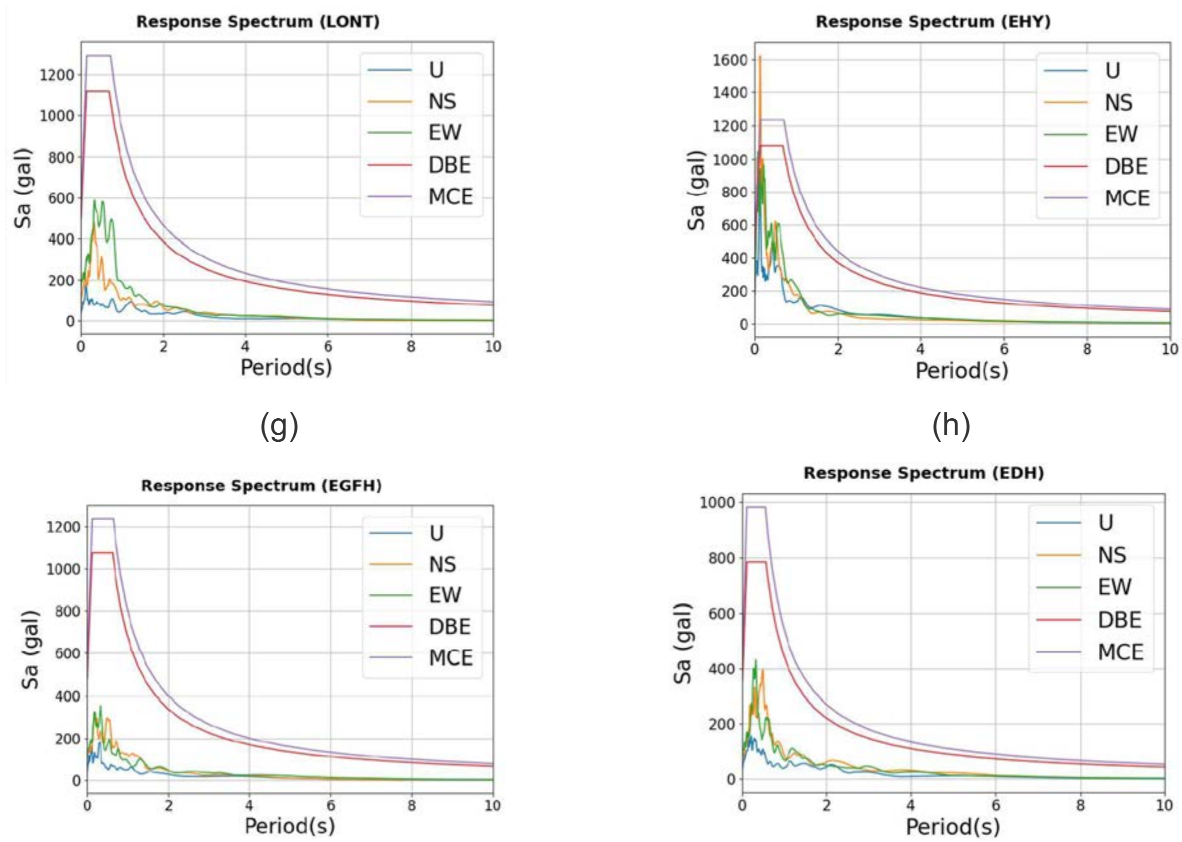
(d)


Response Spectrum (CHK)
Period(s)
U
NS
EW
DBE
MCE

(e)


Response Spectrum (YUS)
Sa (gal)
Period(s)
U
NS
EW
DBE
MCE

(f)



(g) (h)

(i) (j)

Figure 3.3. Comparison of response spectra computed from recorded horizontal (NS and EW) and vertical (U) accelerations at different stations to the elastic design spectrum for the Design Base Earthquake (DBE) and Maximum Considered Earthquake (MCE): (a) Chishang, (b) Yuli, (c) Sea Test, (d) Changbin Testing, (e) Bonanza, (f) Yushan Test, (g) Luye, (h) Hongye, (i) Optical Complex, (j) East River (NCREE, 2022b).

Based on the uniform hazard analysis, the mapped design 5%-damped spectral acceleration at short periods (S_S^D) and at 1 s (S_1^D) have been tabulated for each municipal unit on a village, town, and city level. Figures 3.4 and 3.5 present the distribution of mapped spectral acceleration parameters for the DBE and MCE levels, respectively. Similar to the current US design codes (ASCE, 2016), the site-adjusted spectral accelerations at short periods (S_{DS}) and at 1.0 s (S_{D1}) are obtained by multiplying the site coefficients:

$$S_{DS} = F_a S_S^D,\ S_{D1} = F_v S_1^D$$

where F_a and F_v are given in Table 3.1.

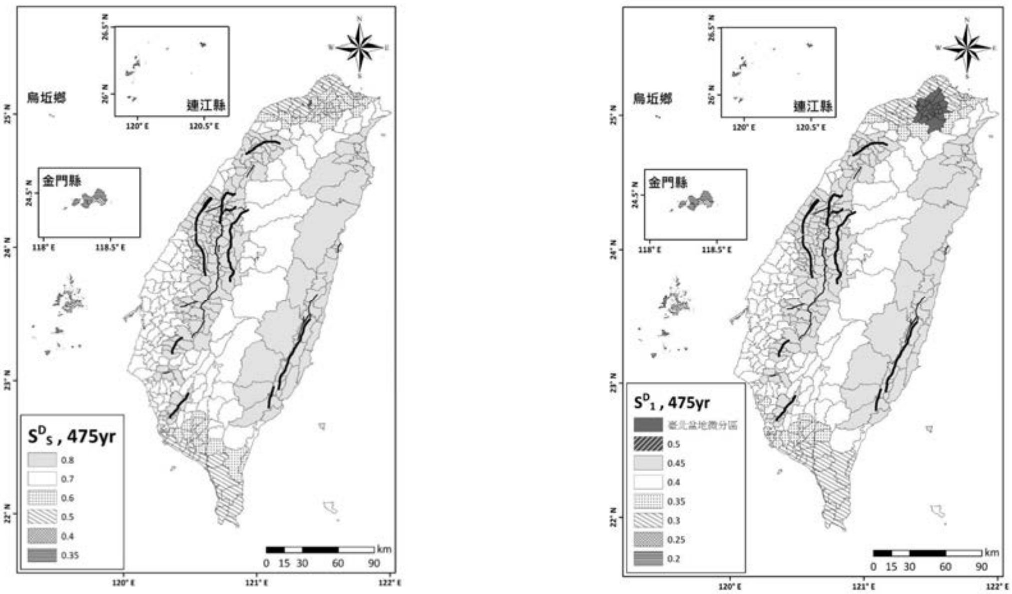


Figure 3.4. Distribution of mapped spectral acceleration parameters for the DBE level (CPA, 2011).

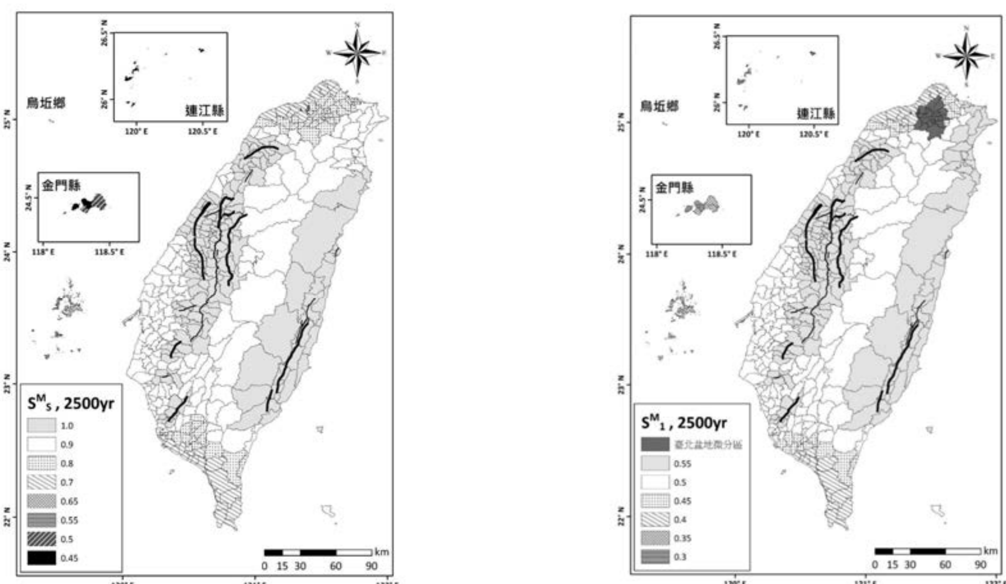


Figure 3.5. Distribution of mapped spectral acceleration parameters for the MCE level (CPA, 2011).

Table 3.1 Values of site coefficients F_a and F_v (adopted from Chai and Teng, 2012)

Site Class	Values of F_a					Values of F_v				
	$S_S \le 0.5$	$S_S = 0.6$	$S_S = 0.7$	$S_S = 0.8$	$S_S \ge 0.9$	$S_1 \le 0.3$	$S_1 = 0.35$	$S_1 = 0.4$	$S_1 = 0.45$	$S_1 \ge 0.5$
Hard site	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Normal site	1.1	1.1	1.0	1.0	1.0	1.5	1.4	1.3	1.2	1.1
Soft site	1.2	1.2	1.1	1.0	1.0	1.8	1.7	1.6	1.5	1.4

Note: S_S and S_1 may be S_S^D, S_S^M, $N_A S_S^D$ or $N_A S_S^M$ and S_1^D, S_1^M, $N_V S_1^D$ or $N_V S_1^M$ for different cases.
Straight-line interpolation is used for the intermediate values of S_S and S_1.

Based on the site-specific spectral acceleration parameters S_{DS} and S_{D1}, the design spectral acceleration S_{aD} for a given period, T, can be obtained by using:

$$S_{aD} = \begin{cases} S_{DS}\left(0.4 + 3T/T_0^D\right) & ; \quad T \le 0.2T_0^D \\ S_{DS} & ; \quad 0.2T_0^D < T \le T_0^D \\ S_{D1}/T & ; \quad T_0^D < T \le 2.5T_0^D \\ 0.4S_{DS} & ; \quad T > 2.5T_0^D \end{cases}$$

with $T_0^D = S_{D1}/S_{DS}$.

The seismic design base shear is expressed as:

$$V = \frac{I}{1.4\alpha_y}\left(\frac{S_{aD}}{F_u}\right)_m W$$

where I is the importance factor, W is the total gravity dead load of the structure, α_y is defined as the first yield seismic force amplification factor that depends on the structure type and design method, and F_u is defined as the structure system seismic reduction factor that can be defined by the allowable ductility capacity R_a and the fundamental period T as:

$$F_u = \begin{cases} R_a & ; \quad T \ge T_0^D \\ \sqrt{2R_a - 1} + \left(R_a - \sqrt{2R_a - 1}\right) \times \dfrac{T - 0.6T_0^D}{0.4T_0^D} & ; \quad 0.6T_0^D \le T \le T_0^D \\ \sqrt{2R_a - 1} & ; \quad 0.2T_0^D \le T \le 0.6T_0^D \\ \sqrt{2R_a - 1} + \left(\sqrt{2R_a - 1} - 1\right) \times \dfrac{T - 0.2T_0^D}{0.2T_0^D} & ; \quad T \le 0.2T_0^D \end{cases}$$

with $R_a = 1 + (R - 1)/1.5$, where R is the structural system ductility capacity that can be found in the seismic design code for most basic types of seismic-force-resisting systems. $(S_{aD}/F_u)_m$ is modified as:

$$\left(\frac{S_{aD}}{F_u}\right)_m = \begin{cases} \frac{S_{aD}}{F_u} & ; \frac{S_{aD}}{F_u} \le 0.3 \\ 0.52\frac{S_{aD}}{F_u} + 0.144 & ; 0.3 < \frac{S_{aD}}{F_u} < 0.8 \\ 0.70\frac{S_{aD}}{F_u} & ; \frac{S_{aD}}{F_u} \ge 0.8 \end{cases}$$

The modified ratio $(S_{aD}/F_u)_m$ is defined to reduce the seismic demand since damping ratios higher than 5% can be considered for structures with short periods due to soil-structure interaction. The constant 1.4 indicates the over-strength factor between the ultimate and the first yield force and is taken as a constant for simplicity (Chai et al., 2009).

3.4 Bridge Codes

Bridge design based on earthquakes in Taiwan has a long history with four major stages. Starting from 1960, the 1960 Highway Bridge Design Specifications had no seismic design guidance, and designers used earthquake coefficients recommended in the Engineer's Manual published by the Chinese Institute of Engineers. Then the 1987 Highway Bridge Design Specifications included horizontal seismic force calculations by a coefficient method and incorporated factors for earthquake zoning, site condition, importance, and fundamental period adjustment. The 1995 Highway Bridge Seismic Design Specifications, which were based on earthquake hazard analysis from seismic codes and research in the US and Japan, define two design objectives. For small to moderate earthquakes, bridges should remain in the elastic range and no significant structural damage should occur. For large earthquakes that have a minimum 475-year return period, collapse of all or part of bridges should be avoided. Although plastic responses were permitted, shear or brittle failure were not allowed. Finally, the 2000 Highway Bridge Seismic Design Specifications incorporated some lessons learned from the 1999 Chi-Chi Earthquake to revise earthquake zoning, peak ground accelerations, response spectra, vertical seismic forces, and failing prevention design (Chang, 2006).

Similar to the seismic design code for building, three demand levels are considered for horizontal seismic forces, Level I (frequently occurring small earthquakes), Level II (10% probability of exceedance in 50 years), and Level III (2% probability of exceedance in 50 years) earthquakes. The mapped design 5%-damped spectral acceleration at short periods (S_S^{II}) and at 1 s (S_1^{II}) have also been tabulated for each municipal unit on a village, town, and city level. Figures 3.6 and 3.7 present the distribution of mapped spectral acceleration parameters for Level II and Level III, respectively.

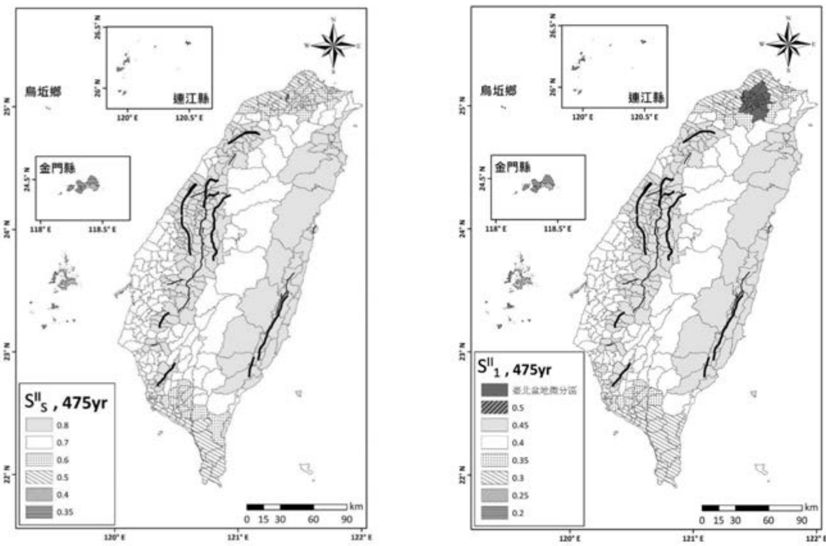


Figure 3.6. Distribution of mapped spectral acceleration parameters for Level II (MOTC, 2019).

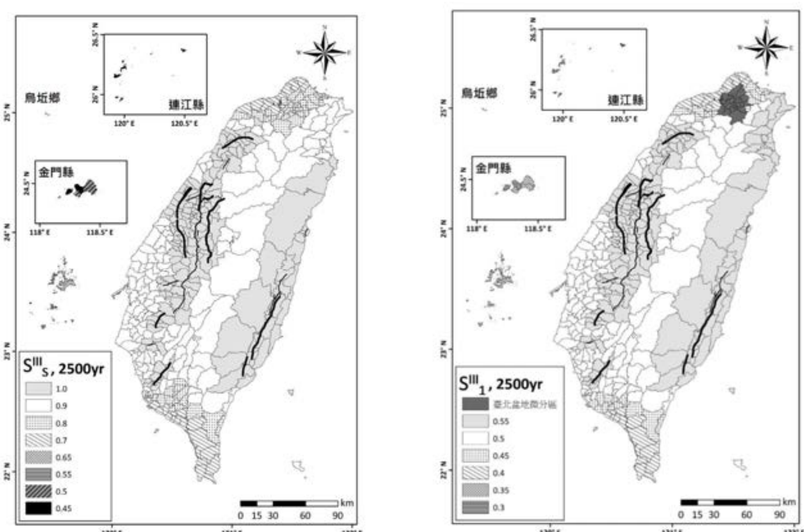


Figure 3.7. Distribution of mapped spectral acceleration parameters for Level III (MOTC, 2019).

The horizontal seismic design force for Level II earthquakes is calculated by:

$$V_{II} = \frac{I}{1.2\alpha_y}\left(\frac{S_{a,II}}{F_{u,II}}\right)_m W$$

where V_{II} is the design force and should not be smaller than $\frac{I}{1.2\alpha_y}\left(\frac{0.4S_{II,S}}{F_{u,II}}\right)_m W$, I is the importance factor, W is the total gravity dead load of the bridge, and α_y is the first yield seismic force amplification factor. $\left(\frac{0.4S_{II,S}}{F_{u,II}}\right)_m$ is calculated by the following equation with $S_{a,II}$ replaced by $0.4S_{II,S}$:

$$\left(\frac{S_{a,II}}{F_{u,II}}\right)_m = \begin{cases} \frac{S_{a,II}}{F_{u,II}} & ;\frac{S_{a,II}}{F_{u,II}} \le 0.3 \\ 0.52\frac{S_{a,II}}{F_{u,II}} + 0.144 & ;0.3 \le \frac{S_{a,II}}{F_{u,II}} \le 0.8 \\ 0.70\frac{S_{a,II}}{F_{u,II}} & ;\frac{S_{a,II}}{F_{u,II}} \ge 0.8 \end{cases}$$

where $S_{a,II}$ is the spectral response acceleration of the bridge and $F_{u,II}$ is the structural system seismic reduction factor calculated both using the fundamental period of the bridge in the direction of design consideration:

$$F_{u,II} = \begin{cases} R_a & ;\ T \ge T_0^{II} \\ \sqrt{2R_a - 1} + \left(R_a - \sqrt{2R_a - 1}\right) \times \frac{T - 0.6T_0^{II}}{0.4T_0^{II}} & ;\ 0.6T_0^{II} \le T \le T_0^{II} \\ \sqrt{2R_a - 1} & ;\ 0.2T_0^{II} \le T \le 0.6T_0^{II} \\ \sqrt{2R_a - 1} + \left(\sqrt{2R_a - 1} - 1\right) \times \frac{T - 0.2T_0^{II}}{0.2T_0^{II}} & ;\ T \le 0.2T_0^{II} \end{cases}$$

$$S_{a,II} = \begin{cases} S_{II,S}(0.4 + 3T / T_0^{II}) & ;T \le 0.2T_0^{II} \\ S_{II,S} & ;0.2T_0^{II} \le T \le T_0^{II} \\ S_{II,1} / T & ;T_0^{II} \le T \end{cases}$$

where $S_{II,S}$ and $S_{II,1}$ are the site-specific spectral acceleration parameters, T_0^{II} is the corner period, and R_a is the allowable ductility capacity, which are defined as:

$$S_{II,S} = F_a S_S^{II}$$

$$S_{II,1} = F_v S_1^{II}$$

$$T_0^{II} = \frac{S_{II,1}}{S_{II,S}}$$

$$R_a = 1 + \frac{(R-1)}{1.5}$$

where F_a and F_v are the site coefficients, and R is the structural system ductility capacity that depends on substructure of the bridge, which can all be found in the Specifications for Seismic Design of Highway Bridges (MOTC, 2019). It should be noted that the site coefficients, F_a and F_v, are slightly different from the values used in the building code.

4.0 Damage to Buildings

4.1 Healthcare Facilities

No reported damage to healthcare facilities were found.

4.2 Schools

A total of 532 schools in 19 counties and cities were affected by the earthquake, as reported on Monday, September 19. Initial damage estimates have reached NT115.7 million (US$3.68 million) (Everington & Taiwan News, 2022). Table 4.1 shows the breakdown of the number of damaged schools by city or county.

Table 4.1. Number of reported damaged schools by city and county (Everington & Taiwan News, 2022).

City or County Name	Number of Schools Reporting Damage	City or County Name	Number of Schools Reporting Damage
Taipei City	31	Nantou County	16
Keelung City	2	Chiayi County	23
New Tapipei City	54	Yunlin County	18
Yilan County	7	Tainan City	44
Hsinchu City	7	Kaohsiung City	115
Hsinchu County	14	Penghu County	3
Taoyuan City	18	Pingtung County	22
Miaoli County	27	Taitung County	46
Taichung City	24	Hualien County	49
Changhua County	12		

Kaohsiung City reported the largest number of school damage with 115 schools. Miaoli County reported the greatest financial losses, estimating damage at NT$16.94 million, followed by Hualien County and Pingtung County with NT$16.7 million and NT$15.67 million, respectively. Not all damage was structural as there was a lot of non-structural damage in the schools that required financial assistance to repair and clean up.

The school with the most losses was the National Yuli High School in Hualien County, which reported damage to the building tiles, cracked walls, damaged ceilings, and partially collapsed walls. The repairs of this school are estimated at NT$43.7 million. Chun-Rih Elementary School in Yuli Township in Hualien County experienced damage to the corridor connecting two buildings.

This corridor was originally two stories and due to column failure, the first story of the corridor collapsed, which is shown in Figure 4.1.

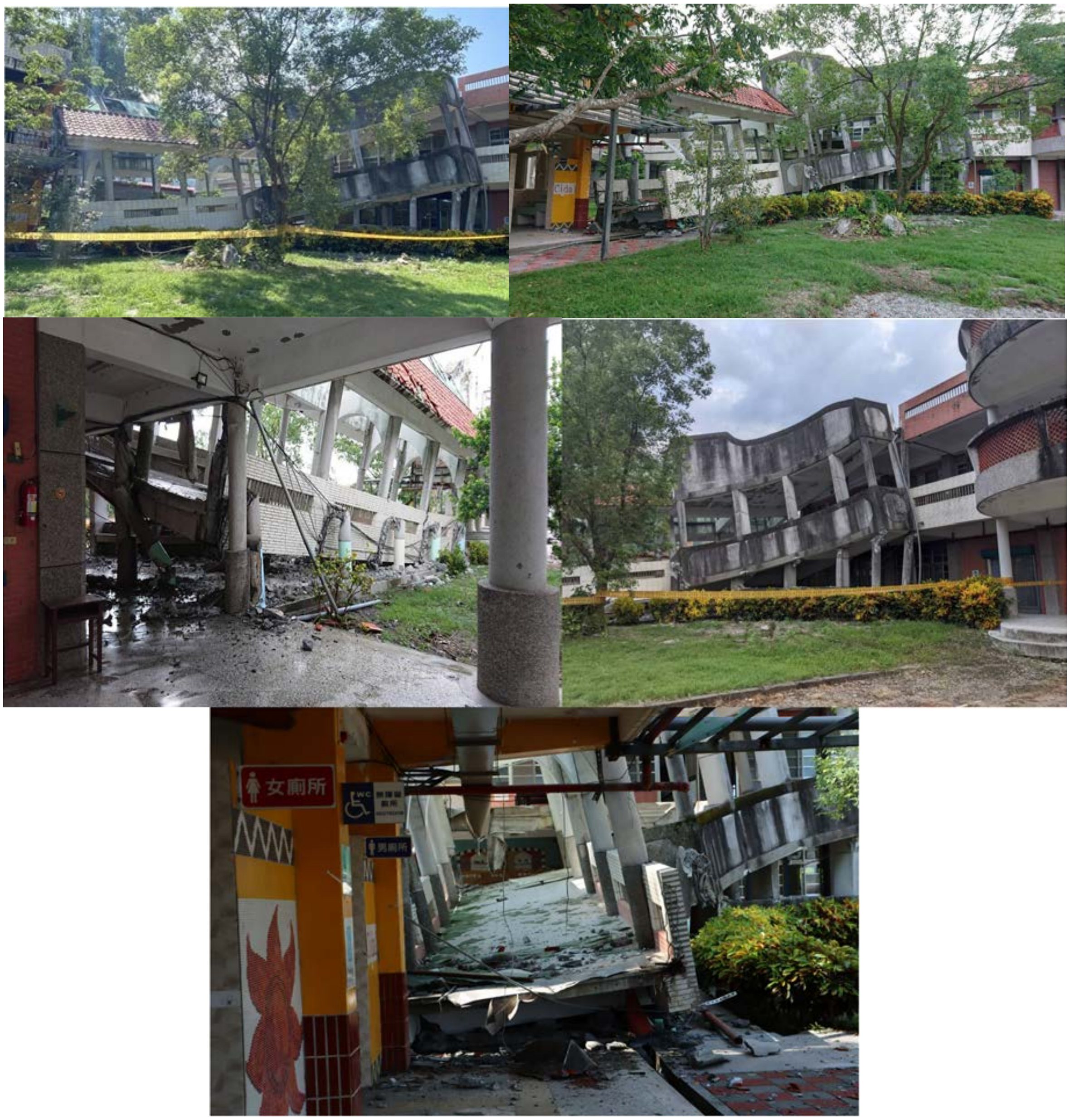


Figure 4.1. Damage to a double level corridor at Chun-Rih Elementary School (Yotaka, 2022; 公視新聞網, 2022; Everington & Taiwan News, 2022).

4.3 Low-rise Buildings

4.3.1. Residential housing

Yuli Township as a population of about 25,000 people and is located in the central Huadong Valley in Hualien County, Taiwan. Yuli Township consists of 15 villages, one of which is Songpuli.

Songpuli's residential buildings were heavily impacted by the earthquake with about 25% of the households being damaged. One of the most severely damaged residential structures had a residual drift of approximately 40 - 50 centimeters, walls collapsed in the kitchen of the house, and there was differential settlement of the ground (鏡新聞, 2022). An example of a damaged house in Songpuli is shown in Figure 4.2. This house has residual deformation after the earthquake and cannot be occupied.

Figure 4.2 House with residual deformation in Songpuli (公視新聞網, 2022; 葉怡瑩, 2022).

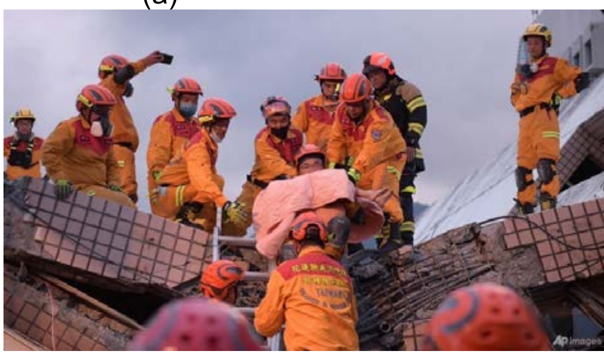
Taitung County Government took stock of the damages in various towns. There were 24 buildings that showed signs of earthquake damage. The owners of these buildings were notified. Damaged homes were also observed in Taitung City, as shown in Figure 4.3. Figure 4.3a is the house before the earthquake and Figure 4.3b is a photo of the collapsed house after the earthquake.

Figure 4.3. House in Taitun city (a) photo of house before the earthquake and (b) photo of house after the earthquake (柯振中、楊漢生, 2022).

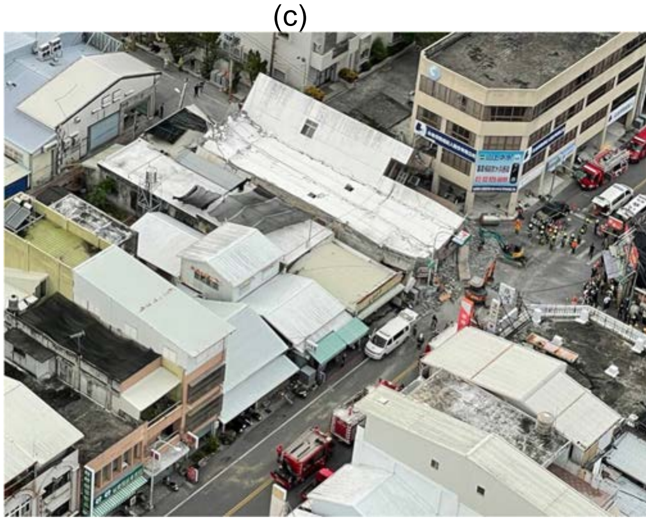
4.3.2. Mixed-use buildings

A three-story concrete building collapsed in Yuli Township (Figure 4.4). The building consisted of a 7-11 convenience store on the ground floor and residential occupancies on the upper two floors (The Associated Press, 2022). Based on the photo of the building before the earthquake (Figure 4.4d) and these two different occupancies, the reason for the collapse can be a soft story, weak story or any other irregularity, such as torsion due to openings at one side of the building, combined with nonductile reinforced concrete characteristics. The photos in Figure 4.4 show that the collapsed building impacted the neighboring building at the first-floor level. If the impact occurred during the strong part of the ground shaking, it likely introduced additional lateral forces into the inertia forces, which could have led to the collapse of the neighboring building. These photos also highlight that identifying and retrofitting vulnerable buildings, such as nonductile concrete buildings, is not only beneficial for the vulnerable building itself, but also it is beneficial for an entire block or neighborhood, which is essential for community resilience.

(a) (b)



(c) (d)



(e) (f)

Figure 4.4. Three story mixed-use building collapse in Yuli town. Collapsed building and rescue efforts showing damaged structural components (CNA, 2022 September 19). (a) - (c) collapsed building state, (d) building before collapse, (e) aerial view of collapsed structure (CNA, 2022 September 20), (f) collapsed building impacting the neighboring building (NPR, 2022)

4.3.3. Industrial facilities

The conveyor belt of a ready mix concrete production facility in Guanshan Township, Taitung County collapsed (Figure 4.5) (CNA, 2022 September 17). This is the location where the one fatality from the earthquake occurred. A worker at the plant was killed during the collapse of this structure. The initial estimated loss of equipment damage was about NT$134million to NT$180 million.

Figure 4.5. Partial collapse in a ready-mixed cement factory in Taitung's Guanshan Township resulting in one fatality (CNA, 2022 September 20).

4.3.4. Commercial and religious structures

Taitung County's Guoguanshan Industrial and Commercial loss amounted to NT$35.5 million. This cost includes both structural and non-structural damage such as damage to computer equipment, cracks in the walls of buildings, and damage to ceiling systems. A Tianxuan Taoist Temple in Yuli collapsed such that the bottom story of the three-story concrete building collapsed thereby leaving the top two stories. Figure 4.6 shows this damage.

Figure 4.6. The Tianxuan Taoist Temple first floor collapsed in Yuli Township (Zhenghong, 2022).

4.4 High-rise Buildings

The tallest building in Yuli Township is a 9-story residential building. A soft-story mechanism occurred in this building such that the first story collapsed. Damage throughout the rest of the building included brick facade damage such that bricks have fallen off the building due to differential settlement (Figure 4.8). The building is now leaning. Elevation differences and ground cracks are observed in the surrounding of this building (Figure 4.8).

(a) (b) (c) (d) (e) (f)

Figure 4.8. Damage to the tallest building in Yuli Township (a) Elevation view of building showing building leaning; (b) View looking up the side of the building showing the building leaning; (c) brick facade damaged due to earthquake; (d) and (e) cracks in the ground surrounding the building (Source:ETTV News); (f) cracks in the wall leading into the parking garage under the building (張寓科 張家寶, 2022).

4.5 Government Facilities (Public Buildings)

At the time of writing, reports of damage to government facilities were unavailable.

4.6 Historical Buildings

According to the Ministry of Culture, Culture and Information, 12 national monuments, 1 municipally designated monument, 2 county-designated monuments, and 8 historical structures were damaged. Except for the partial collapse of Wan'an brick factory kiln in Chishang, Taitung, which is listed as a "historical building", there was no major damage. The partial collapse of this unreinforced masonry building is shown in Figure 4.9.

Figure 4.9. Partial collapse of Wan 'an brick factory kiln in Chishang, Taitung [Photo by Chuan-Mi, Cao (曹釧蜜)].

4.7 Nonstructural Components and Building Content

Common nonstructural component damage included falling ceiling tiles, items falling off shelves in stores, and fallen shelving units. This section is divided by occupancy type to demonstrate common themes of non-structural components across occupancies.

4.7.1. Schools

School damage occurred across the country. This damage varied from shelving falling over to damage to the ceiling tiles. Both of these damages present a life safety hazard for occupants.Non-structural damage occurred at about 148 schools across the country due to the earthquake (Chen & Van Trieste, 2022). Figure 4.10 shows damage to the ceiling of a gymnasium at a school in Pingtung County. Figure 4.11 shows damage to interior walls of the school near a window. It is not clear if these cracks extend beyond the dry wall to the structural components. Figures 4.12 and 4.13 show non-structural damage consisting of items falling off bookshelves and shelving units fall over. At Hualien Three Republics Middle School the septic tank ruptured and flooded the first floor of the building (Yanhua & Sihui, 2022) (Figure 4.14).

Figure 4.10. Damaged ceiling tiles at a school in Pingtung County (CDNS E, 2022).

Figure 4.11. Cracks on walls inside schools (Chen & Van Trieste, 2022).

Figure 4.12. Fallen bookshelves due to the earthquake at Kasuga Elementary School in Yuli Town, Hualien County (Picture taken by reporter Xu Zhenghong) (Sihui et al.,2022).

Figure 4.13. Items fallen off bookshelves and shelving units collapsed at the affected schools in Hualien County (Yanhua & Sihui, 2022).

Figure 4.14. Flood from ruptured septic tank at Yuli Spring Elementary School (Yanhua & Sihui, 2022).

4.7.2. Commercial structures

The ceiling of an indoor badminton court, on the fifth floor of Bade Civil Sports Center in Taoyuan City's Bade District, collapsed (Figure 4.15) (Everington, 2022). The facility had finished installing the lights within the structure one week prior to the earthquake. No one was injured during the collapse although a badminton game was occurring at the time of the earthquake. This demonstrates an example of the need for nonstructural components not only to be functional, but also to remain undamaged to avoid falling hazards and other threats to human life and health.

Ceiling tile damage was also observed in a mall in Kaohsiung City, called Kaohsiung Dream Era (Figure 4.16).

(a)

(b)

(c)

Figure 4.15. Ceiling of the badminton facility (a) before the earthquake; (b) and (c) after the earthquake (Everington et al., 2022; Yilong, 2022).

Figure 4.16. Ceiling tile damage within mall in Kaohsiung City called Kaohsiung Dream Era (Baoguang, 2022).

The collapse of non-structural storage racks occurred within a columbarium (Figure 4.17 and Figure 4.18) located in Taitung. The photo also shows damage to several suspended ceiling panels.

Figure 4.17. Damage due to dynamic overturning of wooden storage racks at a columbarium in Taitung (CNA, 2022 September 18; CNA Southern Local Group, 2022; Manda, 2022).

Figure 4.18. Damage to the columbariums of Matsuura and Changliang in Hualien Yuli Town showing damaged ceiling tiles on the floor and open doors to urn chambers (Photo courtesy of Yuli Town Office) (Sihui, 2022).

In grocery stores and other convenience stores, items fell off the shelves and shelving units fell over (Figure 4.19) this same behavior was observed in other retail stores (Figure 4.20). In the IKEA store in Xinzhuang (Figure 4.21a) and within a mall in Kaohsiung City (Figure 4.21b), sprinkler lines ruptured causing water damage. In commercial structures, damage to the partition walls within hallways were damaged (Figure 4.22).

Figure 4.19. Collapsed -overturned- shelves and fallen products in supermarkets in Chishang, Taitung

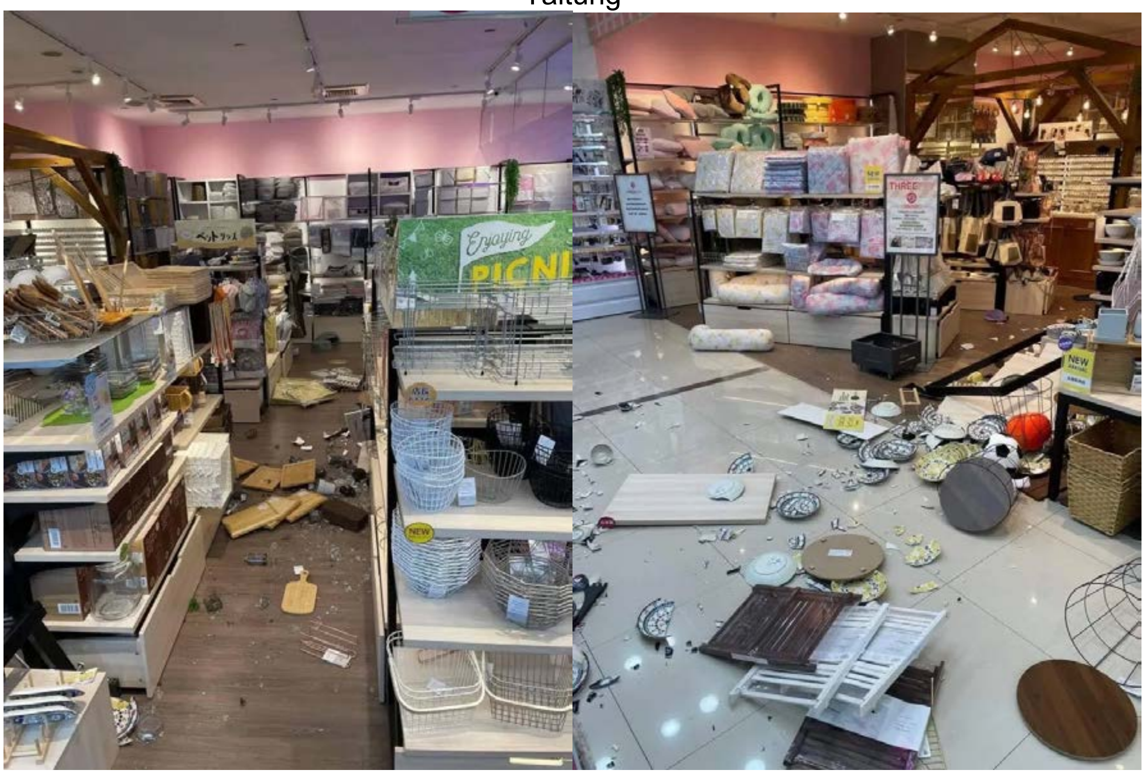


Figure 4.20. Items fell off shelves in a mall in Kaohsiung City

(a) (b)

Figure 4.21. Rupture of sprinkler lines (a) in IKEA in Xinzhuang (Picture originally retrieved from Aixinzhuang, Facebook); (b) in a mall in Kaohsiung City called Kaohsiung Dream Era (Baoguang, 2022; 三立新聞網, 2022; 鐘如庭, 2022).

Figure 4.22. Damage to non-structural walls within a shopping center (CDNS L, 2022).

4.7.3. Elevator impacts

There were multiple reports of people trapped in elevators. A total of 21 reports were made in Kaohsiung and 35 people were rescued from these instances. It is noted that the functioning of elevators is a major requirement for preoccupancy and functional recovery of medium-rise and high-rise buildings.

4.7.4 Industrial facilities

Industrial facilities experienced damage to storage tanks. Specifically the Qiankun Rice Factory and a concrete manufacturing facility. The front and rear equipment of the new Qiankun Rice Factory in Guanshan Town were damaged. The damage consisted of damage to (21) 100-ton low-temperature silos, 6 drying furnaces, and 1 coarse bran furnace line was damaged (Figures 4.23 and 4.24). The bottom of the two 150-ton low-temperature silos in the factory were damaged and overflowed with rice husks. The rice grain conveying line connecting 20 silos in the rear plant had residual deformation after the earthquake. The initial loss was estimated at NT$223 million.

Another rice silo conveying line in Guanshan Town was also damaged, and the loss was estimated at about NT$9 million.The Agriculture Department reported earthquake damage to 25 silos, affecting about 3,400 metric tons of rice. It is estimated that the second phase of rice harvest will be affected by about 570 hectares, accounting for 28% of the 2,042 hectares of rice planting area in Guanshan Town. To assist the rice factory in resuming operations as soon as possible, the Taitung County Government has written a letter to the Agricultural Committee to subsidize the Guanshan Farmers Association and provide low-interest loans to two rice milling factories, so as to carry out post-disaster reconstruction work as soon as possible (地方中心／台東報導, 2022).

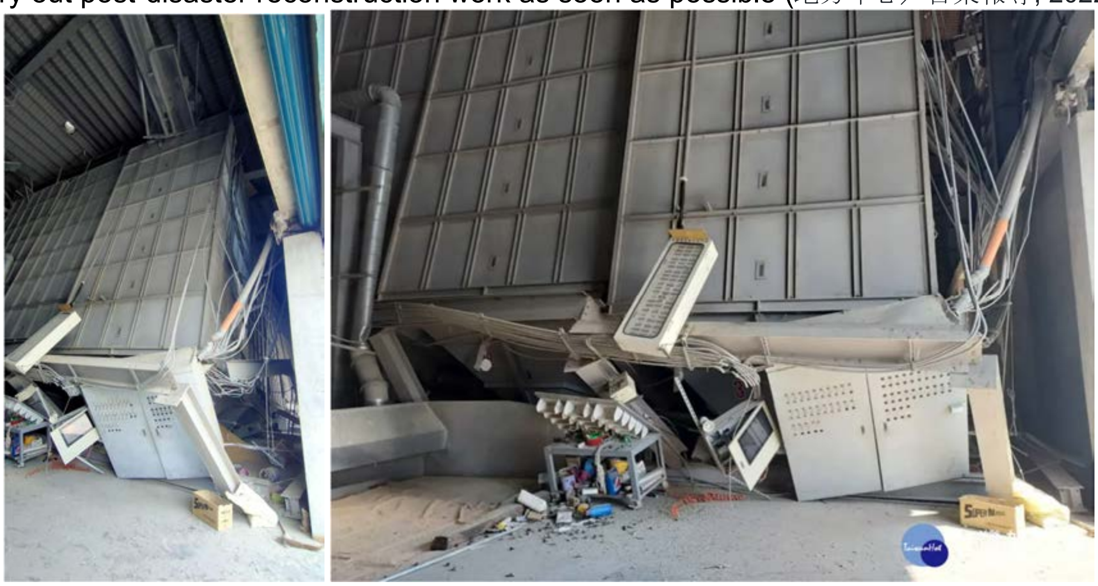


Figure 4.23. Damage to the refrigerated storage and drying equipment of a rice milling plant located in Guanshan Town (地方中心／台東報導, 2022; CNA, 2022 September 17).

Figure 4.24. One of four rice storage tanks that collapsed due to the earthquake at the Farmers Association's Rice milling plant (Xin Qinkun Rice Factory) in Guanshan Township, Taitung

County (a) view at base of the storage tank and (b) elevation view of storage tanks (Congguang, 2022; NCREE, 2022b).

Figure 4.25. Collapsed concrete storage tank next to power lines in Taitung County's Guanshan Township (Shan, 2022).

5.0 Damage to Infrastructure

This chapter presents the observed damage to the electric power and transportation infrastructure.

5.1 Electric Power Infrastructure

Electricity services were briefly disrupted as a result of damaged infrastructure but there were no reports of issues at nuclear power plants on the island. These power outages were due to downed electricity lines caused by landslides near Chike Mountain in addition to approximately 40 electricity poles damaged (Wang & Hsiao-han, 2022). A total of 22,024 households were without power immediately after the earthquake (Li-yun et al., 2022) with a total of 7,073 of those households in Hualien's Yuli Township (Hsien-feng & Lo, 2022), 300 in Lidao (Minzheng, 2022), and neighborhoods in Taipei, New Taipei, Tainan and Kaohsiung also reported blackouts. As of 9/19, power had been restored to all but 445 households.

5.2 Airport and Railway Infrastructure

A canopy at the Dongli station collapsed. The debris from this canopy caused a train derailment of six cars. There were about 20 passengers within the cars, but none were injured (Figure 5.1) (Associated Press, 2022). More than 10 routes of the Taiwan Railway and 3 railway bridges were damaged (Newtalk, 2022). Officials suspended rail services between Hualien and Taitung counties along a 106 km (66 miles) section following damages to overhead power lines, tracks, and multiple railway bridges (Taiwan: Rail, 2022). Services were restored by 9/22, including trains running between Hualien Station and Fenglin as well as between Fuli, Hualien County and Taitung Station (Taiwan: Rail, 2022). However, rail transport disruptions remained along a section of the Eastern Trunk Line in eastern Taiwan as of 9/22 due to collapsed bridges (Gaoliao and Luntian Bridge) (Taiwan: Rail, 2022). In addition, several rail stations remain closed, such as Yuli Station (Taiwan: Rail, 2022).

Several railway track segments buckled during the earthquake (Figure 5.2) (Liao, 2022). Six buckled segments of the railway line in the Hualien and Taitung area were repaired by 9/21, but about 40 broken electricity poles along the damaged section are still being repaired (Liao, 2022). The Minister of Transportation and Communications Wang Kwo-tsai (王國材) inspected the railway damage on 9/19, and estimated that it would take over a month to restore the railway line (Liao, 2022).

(a) (b)

(c) (d)

Figure 5.1. (a) Train derailment at Dongli station in Hualien. Photo taken by Taiwan Railways Administration; (b) - (d) Collapsed train platform canopy at Dongli Station in Hualien County (NowNews, 2022).

Figure 5.2. Buckled rail tracks and collapsed train power lines (Qiongyu, 2022; CNA, 2022 September 20).

5.3 Bridges

The Taiwan Bridge Management System (TBMS) has an inventory of about 28,000 bridges, with approximately 30% of them over 30 years old and another 30% with an unknown construction date. Figure 5.3 shows the age distribution of bridges in the inventory corresponding to each managing agency.

Bridge's age	Freeway/Highway	Railway	City/ County	Total
~10	726	54	1,235	2,015
10~20	2,262	262	3,198	5,722
20~30	1,004	332	4,037	5,373
30~40	971	359	2,752	4,082
40~50	252	408	606	1,266
50~60	61	104	199	364
60~70	18	65	41	124
70~80	9	9	9	27
80~90	6	-	15	21
90~100	-	-	5	5
100~110	-	-	1	1
unknown	16	135	9,214	9,365

Figure 5.3. Age distribution of bridges by management agency (Chuang & Yau, 2017).

Since the creation of the TBMS in 2000, the Ministry of Transportation and Communications (MOTC) has been funding studies to determine decisions of prioritization of bridge maintenance and allocation of maintenance budgets across central and local governments in the country. These studies include finding correlations between bridge deterioration and inspection data; developing prioritization factors based on deterioration, traveler use, and social costs, and developing life cycle costs analysis (Chen, 2007; Chuang & Yau, 2017; Lin, 2007; Safi et al., 2014; Su, 2003; Zhu, 2013).

Currently, in order to determine the structural safety and maintenance needs of the bridges the MOTC has implemented the inspection methodology shown in Figure 5.4. This criteria assigns a 0 to 4 rating to four indices abbreviated as DER&U which stand for D: degree of deterioration, E: extent of deterioration, R: relevancy, and U: urgency for repairing. It is worth noting that as of 2017 Taiwan did not yet have minimum qualifications requirements for inspectors (Liao et al., 2017). This lack of training may lead to overlooking important condition indicators during inspection that only trained professionals could recognize. Furthermore, while some of the research findings have been implemented to improve maintenance actions, there is still much still investigations in the developing stages for the management system.

	0	1	2	3	4
D	Not exist	Good	Fair	Bad	Serious
E	*U/I	<10%	10~30%	30~60%	Over 60%
R	Uncertain	Minor	Limited	Major	Large
U	**N/A	Routine	In 3 yrs.	In 1 yr.	Immediate

*U/I – Unable to Inspect, **N/A – Not Applicable

Figure 5.4. Taiwan's MOTC Bridge Inspection Criteria (Liao et al., 2017)

Several bridges were damaged or collapsed in the earthquake. This section will provide a discussion of these bridges. In total, the bridge damage reported in the media and by government officials include the following (梁國榮, 2022).

- Xinwanlixi Bridge
- Lelexi Bridge
- Xinxiu Guluanxi Bridge
- Gaoliao Bridge (collapsed)
- Luntian Bridge (collapsed)
- Yuchang Bridge
- Yuxing Bridge
- Yuli Bridge
- Wanning Land Bridge (collapsed)
- New Xiugulan River Bridge
- Changfu Bridge
- Lishanli No. 1 Bridge

The location of these damaged bridges with respect to the earthquake epicenter is shown in Figure 5.5.

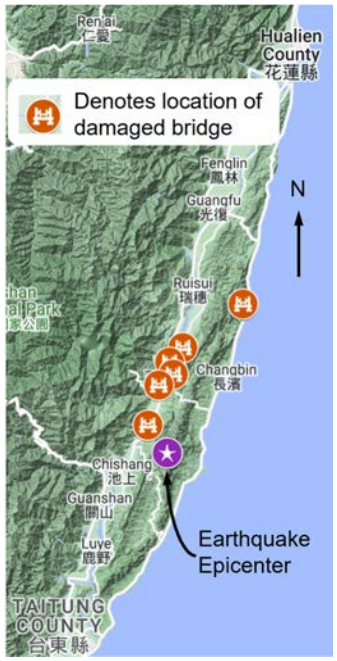


Figure 5.5. Location of damaged bridges with respect to earthquake epicenter.

5.3.1 Railway bridges

Two railway bridges experienced severe damage. These include the New Xiugulan River Bridge and the Wanning Land Bridge. The out-of-plane deformation of the piers of the New Xiugulan River Bridge displaced more than 100 cm. In addition, the Wanning Land Bridge collapsed (中央通訊社, 2022).

5.3.2 Vehicular traffic bridges

According to statistics from the Hualien County 918 Disaster Response Center, the earthquake caused two bridges in Hualien County to collapse, and five bridges to have permanent deformation and heavy damage. Gaoliao Bridge and the Yuxing Bridge collapsed in the earthquake. The Hualien County Government issued a message stating that the earthquake caused damage to most of the piers and columns of the Gaoliao Bridge, causing collapse. The Gaoliao Bridge is the main linkage between Chike Mountain and Yuli Township. Drone footage demonstrated that the entire straight portion of the bridge collapsed in the transverse direction. It is observed from Figure 5.6 that the bridge bents are single-column bents, and the columns collapsed in mixed shear and flexural modes of failure. Because the bridge is very long, the torsional and transverse stiffness values provided by the abutments, if any, become ineffective and the columns essentially behave as cantilevers. Accordingly, the deck serves as a rigid diaphragm to the columns between the in-span hinges without providing much rotational restraint at the top of the columns. Considering the rigid diaphragm constraint provided by the deck and that all columns have similar geometry and longitudinal reinforcement; all columns likely reached their drift capacity almost simultaneously and collapsed. Considering that the bridge is a long bridge with a long period in the transverse direction, displacement demands were large during the shaking, which exceeded the drift capacity. Therefore, the single column bents behaving as cantilevers moving synchronously, without any redundancy and possibility of redistribution. Additional detailed analysis is required to confirm the collapse mechanism of the bridge

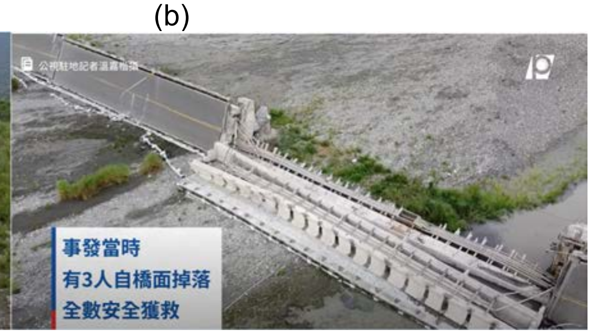
The Yuxing Bridge had a widening construction project that started in 2020. Out of 32 I-shaped beams, four collapsed and 12 had large deformations. There were no casualties due to the collapse of either of these bridges. The Yuli Bridge damage disrupts traffic from Fuli and Taitung as this is the only bridge connecting these two regions.

Deck damage to a number of vehicular bridges was observed (see Figure 5.7). In particular this was for the Yuli Bridge spanning the Xiuguluan River in Hualien County, the Luntian Bridge in Hualien County, and the Baohua Bridge in Luye Township. Vehicles were trapped on both the Yuli Bridge and Luntian Bridge; however, there were no casualties associated with those trapped.

(a)

(b)

(c)



(d)

(e)

Figure 5.6. Gaoliao bridge (a) Before collapse (Photo by reporter Hua Mengjing); (b) - (e) Photos of the Gaoliao bridge after the earthquake (華夢靜, 2022; 華夢靜, 2022; Public Television News Network,2022).

(a) (b) (c) (d) (e)

Figure 5.7. Deck damage to bridges (a) Yuli Bridge (CNA, 2022 September 20); (b) - (c) Luntian Bridge (NCREE, 2022b); (d) collapse of the Luntian Bridge (華夢靜, 2022); (e) Baohua Bridge in Luye Township (CNA, 2022 September 18).

5.4 Roadways

Rockfalls and landslides on the Sixty Stone Mountain Road in Hualien and the Liushishan Road in Fuli Township caused 400 people to be trapped in the mountainous area (Figure 5.8). On the road, people lined up to descend the mountain on September 22 around noon local time once cleared by authorities (CNA, 2022 September 20).

Due to the continuous aftershocks, the Taitung Forest District Management Office closed six forest roads and six hiking trails in the area on September 18, and completed the safety inspection of the trails after the aftershocks slowed down. On September 21, the Forestry Department announced through its official website that four forest roads including Jinping, Wulu, Yanping and Zhiben would be reopened due to the elimination of hazards related to rockfalls. Redstone 2 trails, Jiaming Lake Trail and Guanshan Red Rock reopened on September 22. Other trails such as the Dulan Mountain Trail, the eastern section of Antong Yueling Ancient Road, and the Machinao Trail, continue to be closed due to rockfalls (王瑞琪, 2022). Additional roadway damage includes cracks in the roads and buckling of roads as shown in Figure 5.9.

Figure 5.8. Rockfalls on the Sixty Stone Mountain Road in Hualien (CNA, 2022 September 20; CNA Southern Local Group, 2022 September 18).

Figure 5.9. Roadway damage (a) Crack in the roadway close to the collapsed Kaoliao bridge in eastern Taiwan's Hualien county (Incredible Images, 2022); (b) Buckling of roadway on Dongli Road (NCREE, 2022b); (c) Buckling of road on Provincial Highway No. 9 in Fuli Township (華夢靜., 2022); (d) Buckling of road in Hualien County; (e) Cracking of road near Gaolin Bridge (Public Television News Network, 2022a); (f) Pavement failure (Hicks, 2022); (g) Road damage due to landslide in Huadong, Taitung area. Photo by Kang Zhongcheng (王瑞琪, 2022); (h) Road near Zhuofu Bridge in Zhuoxi Township was severely cracked (CDNS C, 2022).

6.0 Observed Geotechnical Failures

This section provides an overview of geological setting and geotechnical damages.

6.1 Geological Setting

Taiwan is an island composed of Cenozoic geosynclinal sediments more than 10,000 m thick on a pre-Tertiary metamorphic basement. In Eastern Taiwan where the earthquake occurred, the composition is of a Neogene andesitic magmatic arc with a variety of volcaniclastic and turbiditic sediments. The volcaniclastic sediments that make up the basement are Neogene andesitic volcanic units and the turbiditic sediments are flyschoid and turbidite sediments. The Eastern Taiwan region was formed with Miocene andesitic flows, anglomerates, tuffs, and associated volcanogenic sediments forming an igneous complex. Then the layer transitions into turbiditic sandstones, siltstones, mudstones, and conglomerates containing disseminated volcanic materials. On top of that layer is the Lichi melange composed of detritus from the western Asiatic continental margin and the eastern Luzon volcanic arc. On the Southern end of the Eastern coast is a layer of Pleistocene piedmont gravels (Ho 1986). A spatial distribution of different geological conditions throughout Taiwan is shown in Figure 6.1.

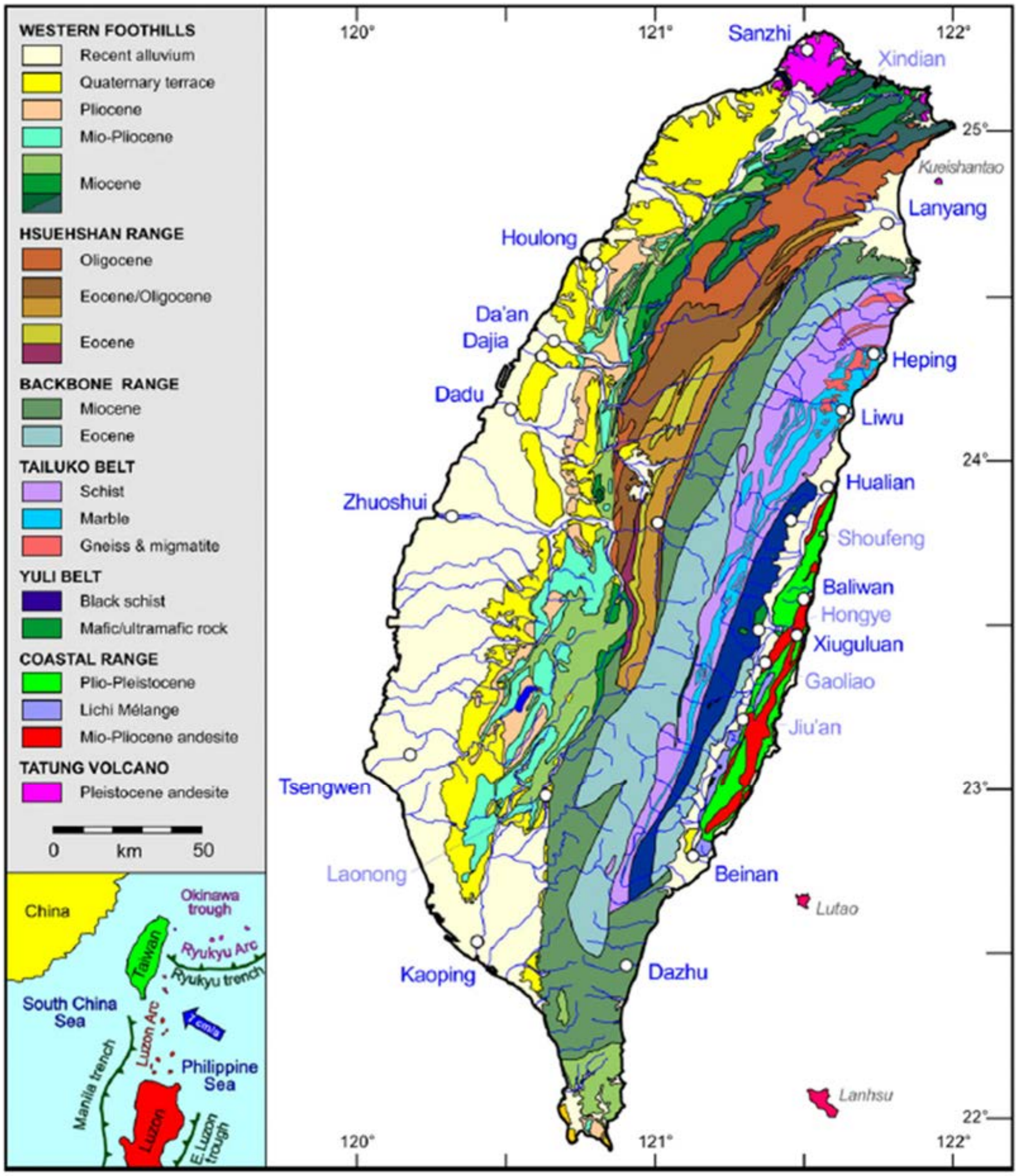


Figure 6.1. Generalized geological map of Taiwan (Garzani and Resentini 2016)

6.2 Liquefaction

As of September 23, there were no reports of liquefaction due to the earthquake.

6.3 Building, Foundation, and Pavement Damages due to Ground Failure

Observations of cracking of mat foundations, pavements, and ground uplift were reported. Pavement cracking was also observed through roadway damage (Section 5.4). The pavement cracking shown in this section is due specifically to ground failure. Figure 6.2 shows pavement cracking around where the Central Range Fault is located in the Longitudinal Valley. These cracks could be indicative of segmentation of the faults. Further surface rupture was seen on sports fields, including deformation of a track in Yuli Township (Figure 6.3a) and surface rupture on a baseball field (Figure 6.3b). Both of these occurred in Yuli Township. Additional cracks in foundations due to ground failure are shown in Figure 6.4. There were no reports on the locations of these damages.

Increase in lateral earth pressures caused structural damage in two cases. The first consisted of lateral pressure causing damage to the Gaoliao Bridge abutment, which subsequently contributed to the collapse of this bridge (Figure 6.6). Damage to a retaining wall along Highway 9 in the Longitudinal Valley was due to increased earthquake pressure on the retaining wall (Figure 6.7).

Figure 6.2. Segmentation of faults in the Longitudinal valley potential to be distributed thrust and strike slip movements (Huang, 2022)

Figure 6.3. Surface rupture on sports fields (a) Running track at Yuli Township (Yu, 2022 a) and (b) En echelon cracks on the baseball field in Yuli Township (Yu, 2022 b)

(a)

(b)

(c)

(d)

Fig. 6.4. Additional foundation damage due to ground failure (a) Crack in foundation (Lee, 2022 a); (b) Crack in courtyard flooring (Lee, 2022 b); (c) Observed separation of foundations with visible rebar (Yongbo & Yuhan, 2022); (d) Pavement failure due to ground failure (Yen, 2022)

Figure. 6.5. Vertical crack formation on the roadway forming headscarp of the landslide at Fuli township Hualien. (Liu, 2022)

Fig. 6.6. Collapse of the bridge abutment and the excessive lateral movement of the retaining wall contributed to the collapse of the Gaoliao Bridge in Hualien (Chenghan, 2022)

Figure. 6.7. Failure of the retaining wall along Highway 9 in the Longitudinal Valley(Yen, 2022)

6.4 Sinkholes

There were no reports of sinkholes.

6.5 Landslides

Landslides occurred throughout Taiwan due to the earthquake. Below is a list of the landslides collected through media sources and in-field reporting. Figure 6.7. shows the Landslide map developed by USGS. Multiple mountain roads were blocked by landslides, trapping tourists in the mountains. There was a quick response to clear out the roads, but the response was hampered by aftershocks (Public Television News Network, 2022a). About 3,400 tourists were trapped on Chike Mountain due to roads blocked from landslide debris and rockfalls. Meishankou and Xiangyang road was blocked due to landslides. The debris was cleared; however, additional landslides occurred during aftershocks. The road was scheduled to be reopened on September 19; however another landslide occurred, causing the reopening to be delayed. Several more aftershocks caused more delays (Public Television News Network, 2022b). Rockfalls occurred on a Sixty Stones Mountain road that also experienced surface road ruptures and collapsed power lines. As of September 18, the road was still damaged but open enough to evacuate tourists (Public Television News Network, 2022b). Photos of these rockfalls and landslides are shown in Figure 6.9.

- Hualien County Yuli Township.
- Meishankou and Xiangyang Road. Additional landslides occurred here in aftershocks.
- Sixty Stones Mountain Road (rockfalls)
- Chikeshan Industrial Road
- Mount Liushishi in Hualien (rockfalls and landslides)
- Pingtung's Jiufawan Road
- Orange Mountain in Chenggong Town
- Luye Luming section of the Taiwan-Ninth Line

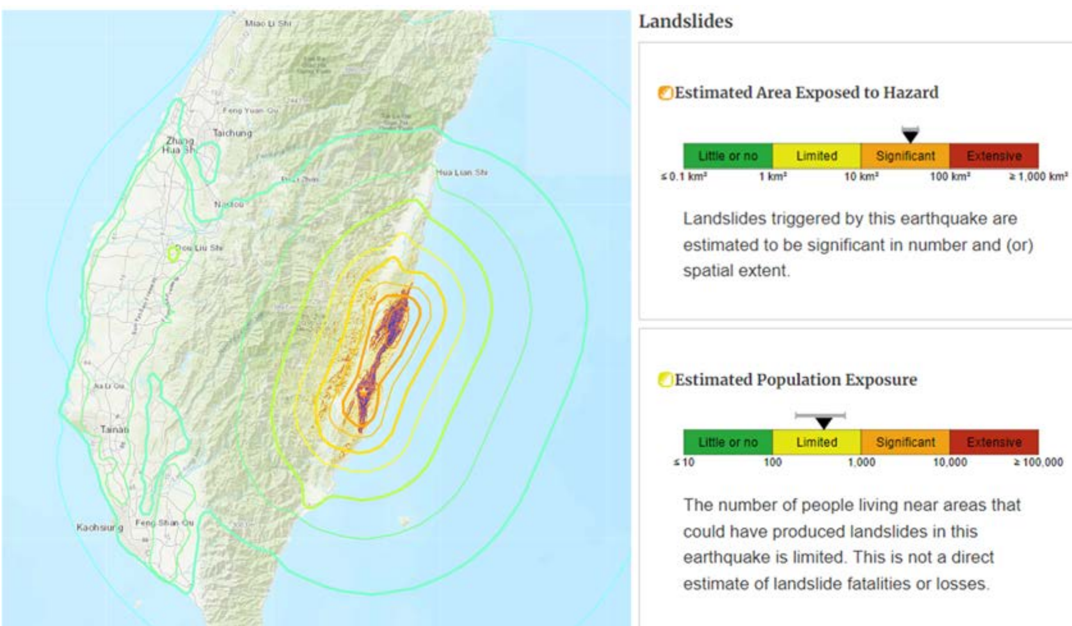


Figure 6.8. Landslide map developed by USGS. The number and/or spatial extent of landslides is estimated as significant, while the number of people affected by landslides is estimated as limited.(USGS, 2022)


(a)

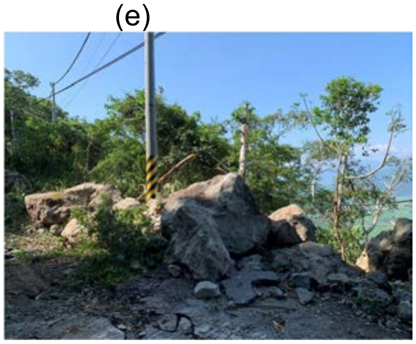

(b)

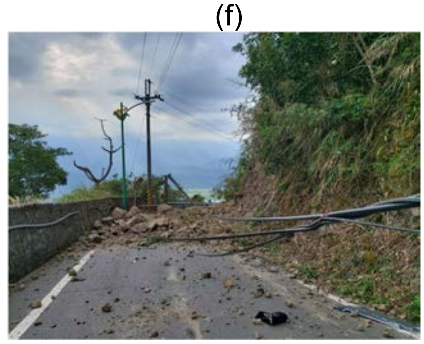

(c)

(d)


(e)


(f)


(g)


(h)

(i) (j)

Figure 6.9. Landslide debris (a) Hualien County's Yuli Township (Shan, 2022); (b) Nanheng Highway, between Meishankou and Xiangyang (Public Television News Network, 2022 b); (c) Chikeshan Industrial Road (Xuesheng, 2022); (d) Rockfall on Sixty Stones Mountain Road (Radio Taiwan International, 2022); (e) Repair of Sixty Stones Mountain Road (Radio Taiwan International, 2022); (f) (Radio Taiwan International, 2022), and (g) Rockfall and landslide observed in Mount Liushishi in Hualien (Liu, 2022 a); (h) Chikeshan Industrial Road (CNA, 2022); (i) Pingtung's Jiufawan Road (CNA-南部地方組, 2022); and (j) Luye Luming section of the Taiwan-Ninth Line (*Taiwan Posts English* 2022)

6.5.1. Photos taken during active landslides

Citizens throughout Taiwan posted videos and photos of landslides taken while they were occurring. This section aggregates these photos for use by researchers. All of these landslides are discussed within the main section and listed at the beginning of the section.

(a)

(b)

Figure 6.10. Rockfall and landslide at Sixty Stone Mountain (a) (Ren, 2022) (b) (Photo captured by Henry Hsu)

Figure 6.11. Landslide occurred in Orange Mountain in Chenggong Town, Taitung city (2022)

7.0 Current Conditions and Access

7.1 Power Outages

As of September 19, within one day after the earthquake, power had been restored to all but 445 households.

7.2 Water Disruption

A total of 4,842 households lost access to water due to the September 18th earthquake (Huang Li-yun et al., 2022). Approximately 3,500 of these are located in Fuli and Yuli Townships. Temporary water towers are being erected and households without water are relying on at-home water storage tanks in the interim (Public Television news Network, 2022c). Any households affected by lack of access to water due to the earthquake or aftershocks are exempt from water bill payments in the current post-earthquake period. Basic fees are waived and bills are exempted if the households apply for water resumption. The water municipality provided a notice to customers to be aware of potential water leaking out of pipes (CDNS E., 2022).

- September 19: The Taiwan Water Corporation erected temporary water towers in residential areas for residents. Water is manually pumped in by water trucks supplied by the Taiwan Water Corporation.
- September 20: 1,801 households are still without access to water (Li-yun, 2022)
- September 21: 962 households in the Hualien area are still without water. (中央通訊社., 2022)

Specific damage to water infrastructure includes rupture of a potable water pipe below Kaixuan Road, located next to the Fengshan Zhongzheng Preschool (Figure 7.1). Around 100-200 people were affected by this pipe damage, with nearby residents reporting the water from the tap was yellowish. (Source: PTS https://www.youtube.com/watch?v=jBCsQ09JDvU)

Some aboriginal areas in Taitung have lost both water and power. To provide health care and water to these populations, about 480 health stations were opened by the Aboriginal Committees (歐陽夢萍, 2022).

Figure 7.1. Repair of water pipes in Hualien following the earthquake (Yourong, 2022)

7.3 Cellular Outage

No reports of cellular service outages were found.

7.4 Post-earthquake Safety Structural Evaluations

7.4.1 Bridge Inspections

There are 356 bridges in Taitung county and inspections commenced immediately post-earthquake. There are currently no reported problems with the highways. (Newtalk, 2022b). For additional investigations of the bridges, the Ministry of Transportation is planning for a professional consultant company to conduct investigation and testing of bridges on 9/27 to begin planning for emergency repairs (中央通訊社, 2022).

7.4.2 Building Inspections

The Construction Administration office coordinated with the National Architects Association and the Civil Engineers Association to dispatch 44 people to participate in the emergency assessment of buildings. The number of red-tagged buildings and buildings of concern are shown in Table 7.1. As of September 21, two buildings had been demolished. All emergency assessments of buildings in both counties were completed by September 21 (Xu, 2022).

Table 7.1. Breakdown of building tagging by County as of 8 PM (local time), 9/21 (中央通訊社, 2022).

Building Label	Hualien County	Taitung County
Buildings of concern (yellow or red tagged)	160	53
Red tagged	17	10

7.4.3 Water and Lake Inspections

After the earthquake, the Seventh River Management office immediately inspected any dykes in regions that experienced ground shaking equivalent to a magnitude 4 or higher earthquake through unmanned aircraft and on-site visual inspections. Water distribution structures in Qishan, Liugui, Taoyuan, and Pingtung City were also inspected. For high-risk sections such as the Linyuan embankment levee structure, non-destructive testing equipment was deployed (Figure 7.2). Inspections also occurred at a project under construction at the Sanye Creek in Tainan city (黃副主任, n.d.).

In addition to the physical infrastructure inspections, several lakes were inspected (Lushan, Toukeng Yexi Confluence, Caoling, Chexinlun and Heliuping) in addition to the Zhuoshui River Basin. Aerial photography surveys were deployed in regions with higher ground accelerations, such as the Chen Youlan River and the Sheqiao river upper stream. No significant damage has been reported in the Zhuoshui River Basin, and constant monitoring post-earthquake will be conducted via CCTV networks and local volunteers (蔡榮宗, 2022).

Figure 7.2. Non-destructive testing of Linyuan Embankment (黃副主任, n.d.)

7.5 Business and Economic Disruptions

No semiconductor manufacturing companies were damaged, despite temporary shutdown of foundry equipment due to automatic earthquake triggering shutdowns. All three science parks in Hsinchu, Taichung, and Tainan had no major damage from the earthquake. No water or power supply was interrupted to these facilities (Lin, 2022).

Due to earthquake damage of the mountain roads in the Sixty Stone Mountain area, the Orange Day-lilies tourist season was prematurely ended. This season normally lasts through the end of September. Local business owners are noting a 50-60% loss of potential earnings as the damage was too severe to continue tourism operations on the mountain (Waksman, 2022). It is estimated that the local businesses will lose about 2,000 tourists/day for the remainder of September (民視新聞網, 2022).

Local agricultural products that are grown in Chike Mountain and Sixty Stone Mountain will be impacted by the road damage along the mountain from the earthquake. About NT$200 million is estimated for agricultural losses. Disaster cash relief is being developed for these businesses (Source: 民視新聞網).

Hotel room cancellations have begun in Hualien due to fears of another large quake within the coming month (Public Television News Network, 2022c). In Taitun, premature check-out of hotel rooms have reached 50% as of September 21. To provide support to the tourism industry, travel subsidies of NT $10 million have been announced by the Taitung County Mayor (Newtalk, 2022c).

Economic impacts due to the rice milling factory damage in Taitung County's Guanshan Township an estimated loss of about NT $70 million (歐陽夢萍, 2022). The total industrial and commercial loss in Taitung County's Guoguanshan is estimated to be about NT $7.95 million, including damage to computer equipment, cracks in the walls of buildings, and damage to the ceilings (CDNS E, 2022).

7.6 Road conditions

The Guluanxi Bridge repair is estimated to take more than 2 years. Roadways in the Hualien area are being repaired. Figures 7.3 and 7.4 show the road repair sections on September 20 and September 22, respectively.

Figure 7.3. Taken at 9/20/2022 7:52PM PST from https://168.thb.gov.tw/thb168 showcasing road conditions in the Hualien area. Red barricade icon is showing "under construction", while orange is showing slightly more congested traffic flow.

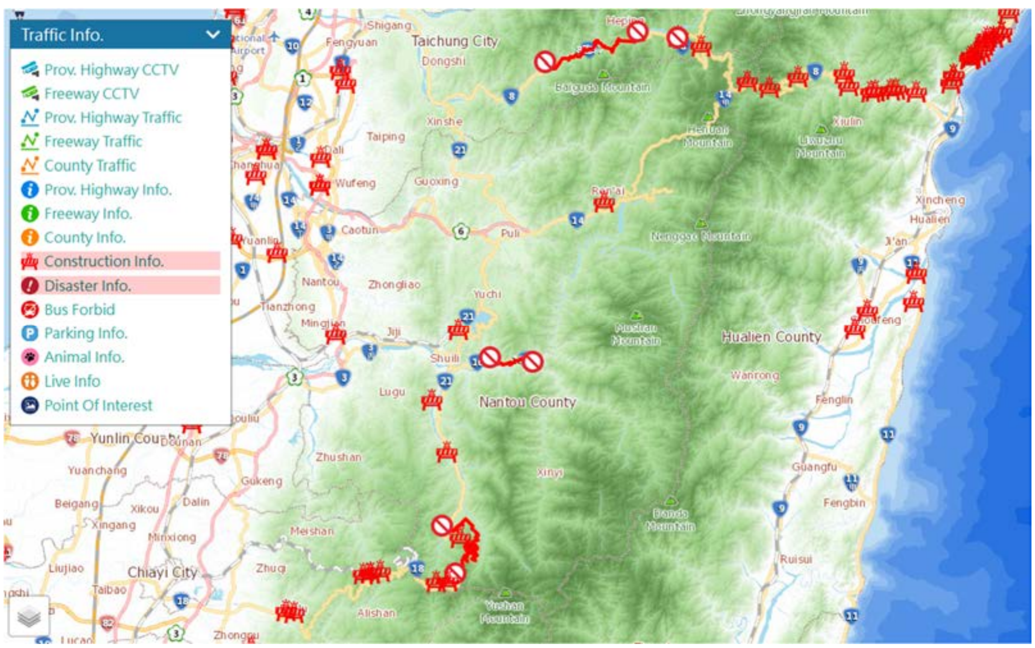


Figure 7.4. Taken at 9/22/2022 3PM PST from https://168.thb.gov.tw/thb168 showcasing road conditions in the Hualien area. Red barricade icon is showing "under construction", while red roads are currently down due to the earthquake.

The two train routes "Hualien to Yuli" and "Taitung to Fuli" will be repaired so that the original disaster-damaged rail section will be reduced from 150.8 km to 18.8 km. The northbound route is targeted to be open to rail traffic before the end of September and there is an alternate route from

Yuli to Fuli along the Southeast side of Taitung. The remaining 18.8 km will be connected via a shuttle bus transfer.

8.0 Video Documentation

Post building collapse video of mixed-use 7-eleven building: https://news.pts.org.tw/live/6326c6757283d50f9f7c13fa.

Video overview of tallest building in Yuli Township: https://www.youtube.com/watch?v=dXjhn5EBCPk

Video of ceiling collapse of Bade Civil Sports Center in Taoyuan City: https://www.facebook.com/groups/147881205898665/posts/1325131751506932/.

A video of the Dongli station during the earthquake can be seen using the following link: https://udn.com/news/story/123030/6627558?from=udn-relatednews_ch2

Video documentation of the geotechnical impacts described in this section can be found in the following links:

- https://www.youtube.com/watch?v=mKhwWXRaPQc
- https://www.newsflare.com/video/516929/taiwan-earthquake-cracks-and-buckles-roads
- https://www.youtube.com/watch?v=GvEjATrFnrA&t=12s

9.0 Summary and Recommendations

On September 18th, 2022, at approximately 2:44 pm local time, a Moment Magnitude (M_w) 6.9 earthquake struck 42.7 km north of Taitung City, in southeastern Taiwan. Damage was observed through Hualien and Taitung counties to buildings and infrastructure in addition to rockfalls and landslides. Based on the information gathered by this PVRR, the following are recommendations for future study.

Study of the operation and response to the Early Warning System: Taiwan has operated an Early Warning System (EWS) in Hualien County since after the 1999 Chi-Chi Earthquake. For the last 20 years this earthquake EWS has been instrumental for the response phase of earthquakes. This event provides an opportunity to learn about technical challenges and operational aspects of the early warning system in addition to public response to the warnings. Specifically, why the EWS did not stop the train going through Dongli Station and thereby resulted in derailment of the train when debris from a canopy collapse hit the train.

Study of the behavior of reinforced concrete bridges: This earthquake caused substantial damage and collapse of multiple reinforced concrete bridges used for both vehicular traffic and rail. Damage to transportation infrastructure can have a severe impact on the economy given increased traffic time and transportation of goods and services. Given the rigor of Taiwan's seismic codes, this event provides an opportunity to learn about the seismic behavior of these bridges, repair and retrofit strategies, and the impact of bridge damage on traffic patterns throughout the region.

Study of landslides and rockfalls: This earthquake caused major landslides and rockfalls throughout the impacted region and therefore provides an opportunity to study the triggering effects towards such damage and the impact of this damage on the functionality of the region itself. Hualien County's economy relies on ecotourism within the mountain regions during the months of August and September. The earthquake effects blocked roads thereby impacting this industry for the remainder of the season, and also trapping tourists.

Study of non-structural components: There was a variety of impacts to non-structural components in various building occupancies. However, common themes of these damages occurred across occupancies such as damage to ceiling systems and shelving units. Therefore, this earthquake provides an opportunity to study the behavior of these non-structural components in buildings throughout the impacted regions, repair strategies, and repair times.

Identification of vulnerable buildings: Building damage in this earthquake was more prominent for non-ductile concrete buildings. This highlights the importance of developing methods for identifying specific nonductile concrete buildings that are vulnerable to collapse, such that their retrofit can be prioritized. The mandatory retrofit programs under several ordinances of the City of Los Angeles (LADBS, 2022), which requires the retrofit of pre-1978 wood-frame soft-story buildings and nonductile concrete buildings, is a great initiative in this regard, which should be adopted by other cities in the US and other countries.

Earthquake sequences: Similar to this earthquake, sequences with consequent large magnitude events separated by short time intervals have been occurring at different parts of the world in the past years. The cumulative effects should be characterized and considered in the design codes of buildings and other infrastructure systems. The ground motion data recorded during this event is beneficial for this purpose. To enable the study of the effects of earthquake sequences, it is recommended to consider documenting the ground motion time series at a particular station in a collocated manner in relevant ground motion databases.

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