Bulletin of the New Zealand Society for Earthquake Engineering, Vol. 50, No. 3, September 2017

THE 2016 MEINONG TAIWAN EARTHQUAKE: LEARNING FROM EARTHQUAKES REPORT

Richard S. Henry[1], Bo-Yao Lee[2], David McGuigan[3], John Finnegan[4] and Gordon Ashby[5]

(Submitted *October 2016*; Reviewed *April 2017*; Accepted *May 2017*)

ABSTRACT

The M_w 6.4 Meinong earthquake occurred on 6 February 2016 in the southern region of Taiwan. The earthquake caused significant damage in and around Tainan city, with a number of collapsed and severely damaged buildings and 117 deaths. A five-member Learning from Earthquakes (LFE) team visited Taiwan approximately one month after the earthquake, with particular focus on learning from changes to design practice and seismic mitigation efforts following the 1999 Chi-Chi earthquake in Taiwan. Land damage was generally modest with liquefaction and slope-failures observed in a limited number of locations. Some notable instances of liquefaction-related foundation settlement and tilting occurred in areas associated with historical filling. Following the earthquake, the Taiwanese government publically released liquefaction hazard maps that will have a significant impact on public awareness and land values. The observed structural damage was characteristic of non-ductile and poorly configured buildings. The collapsed buildings all contained irregularities and soft-storeys. The majority of older mixed-use buildings performed adequately, but severe column failures were observed in several taller apartment buildings constructed in the 1990s. The performance of schools and district offices provided valuable insight into the successful implementation of seismic assessment and strengthening programmes. A comparison of existing and strengthened buildings showed that efficient retrofit solutions can reduce the risk posed by critical structural weaknesses and improve the safety and resilience of these buildings. A similar strategy could be implemented for common critical structural weaknesses in New Zealand buildings.

INTRODUCTION

At 3:57 am on 6 February 2016 the southern region of Taiwan was struck by a M_w 6.4 earthquake. The earthquake was centred at a depth of around 14.6 km in the Meinong District of Kaohsiung, Taiwan. The earthquake caused damage over a wide area including the collapse of a number of buildings. A total of 117 people were killed as a result of the earthquake, with 115 of the fatalities occurring as a result of the collapse of one apartment building complex.

Taiwan has a history of severe earthquakes and an NZSEE reconnaissance team previously visited Taiwan following the 21 September 1999 Chi-Chi earthquake [1]. This devastating earthquake killed over 2400 people and led to the destruction of over 50,000 buildings. The NZSEE reconnaissance team report provided extensive background on the geologic and seismic aspects of Taiwan as well as the earthquake impacts. The lessons from the Chi-Chi earthquake resulted in changes to the seismic provisions of structural design standards and the development of seismic mitigation programmes, such as that implemented for existing school and local government buildings.

A five person NZSEE delegation travelled to Taiwan for 7 days from 9-16 March 2016, just over a month after the Meinong earthquake. Following two days of meetings with central government agencies and research institutions in Taipei, the team travelled to the affected areas in the southern region of Taiwan.

This paper provides an overview of the observations and findings from the NZSEE Learning from Earthquakes mission and lessons from this earthquake that are relevant to New Zealand.

MISSION OBJECTIVES

Prior to travelling to Taiwan, key objectives for the mission were prepared by members of the NZSEE Learning from Earthquakes Committee. Due to the isolated nature of the earthquake impacts and the timing of the mission, a number of damaged sites had already been cleared. The focus was therefore on learning from wider aspects of the earthquake impacts and the effectiveness of initiatives that commenced following past earthquakes.

The primary objectives of the mission were:

- To observe the effectiveness of post 1999 building policy, demonstrated by the performance of buildings built post-1999.
- To observe the effectiveness of the seismic improvement programmes, predominantly on existing (pre-1999) school and local government buildings.
- To gain an understanding of the responsiveness of government and the local and national emergency service providers to the event.
- To understand current initiatives being considered in Taiwan to identify, assess and improve existing buildings.
- To understand the wider initiatives that Taiwan has established to better understand the effects of earthquakes by developing dedicated research facilities.

---

[1] *Corresponding Author, Senior Lecturer, University of Auckland, rs.henry@auckland.ac.nz (Member)*
[2] *Senior Policy Manager, Ministry of Education, Wellington, Bo-Yao.Lee@education.govt.nz (Member)*
[3] *Deputy Chief Engineer, Ministry of Business, Innovation & Employment, Dave.McGuigan@mbie.govt.nz (Member)*
[4] *Technical Director – Buildings, Aurecon, John.Finnegan@aurecongroup.com (Member)*
[5] *Senior Geotechnical Engineer, Tonkin & Taylor, GAshby@tonkin.co.nz (Member)*

The NZSEE delegation also had the opportunity to visit two museums dedicated to the 1999 Chi-Chi earthquake. The museums preserved the impact and legacy of this earthquake and provide education and information for the public on the preparedness and resilience measures that have been made for future earthquakes.

BACKGROUND

Taiwan is an island located approximately 180 km off the southeast cost of mainland China. It has a population of approximately 23.4 million people on a land area of 36,000 km^2, around 14% of the land area of New Zealand [2]. Approximately 7 million (or 30%) of the population reside in the Taipei metropolitan area at the northern tip of Taiwan, and a further 1.3 million reside in the Tainan metropolitan area that was most effected by the Meinong Earthquake. Similar to New Zealand, Taiwan is located on an active plate boundary within the 'Ring of the Fire' and experiences frequent earthquakes. It is also prone to severe typhoons that could trigger serious flooding and landslides[1].

Taiwan has a stable modern economy having undergone rapid industrialisation in the latter part of the 20th century. This development was focused on high-tech industry, such as the production of micro-electronics and computer hardware. This rapid growth has had a significant impact on the population and construction in urbanised areas.

Tectonic and Geological Setting

Taiwan is located at the meeting of the oceanic Philippine Sea Plate (PSP) from the east and the continental Eurasian Plate (EP) from the west. The majority of the island of Taiwan is under compressive stress due to the convergence of these two plates at a rate of around 82 mm/year [3]. This tectonic action has formed the mountainous region along the east coast, which runs virtually the entire length of Taiwan, as shown in Figure 1. The northern part of the island is adjacent to an area where the PSP is subducting beneath the EP, which forms the off shore Ryuku Subduction Zone. To the south of the island the EP is subducting beneath the PSP.

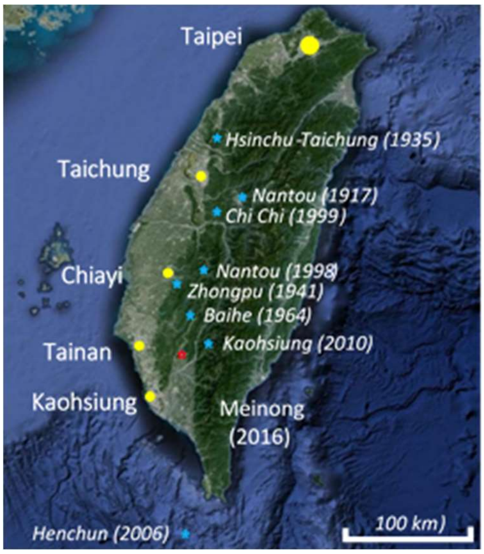


Figure 1: Taiwan geography and significant past earthquakes (Source: Google Earth 2016).

The western parts of the island are relatively low-lying and where the main centres of population are. In the south, the underlying geology comprises Miocene and Pleistocene marine sedimentary rocks overlain by Holocene marine sandstone of the Tainan Formation. Folding and faulting of these rocks have resulted in local highs (tablelands) and intervening basins (lowlands) that have been infilled with marine estuarine deposits of sand and silt (Dawan Formation) that is reportedly between 2750 and 300 years old and on the order of 20 to 40 m thick in places [4]. The lowland areas have generally been mapped at a regional scale as being potentially susceptible to liquefaction.

Past Earthquakes

Not surprisingly, given the tectonic setting, Taiwan is a country with a high level of seismicity. Taiwan has experienced a large number of major earthquakes, with 48 that resulted in loss of life during the 20th century. There have also been 90 events of magnitude greater than 6.4 recorded within 250 km of the Meinong earthquake over the last 100 years [5]. Examples of previous destructive earthquakes (locations labelled in Figure 1) include a M_W 5.7 earthquake 70 km to the north in July 1998 (Nantou) causing 5 fatalities; a M_W 7.0 earthquake in December 2006 located 120 km to the south (Henchun) causing 2 fatalities. The Chi-Chi earthquake (also Jiji, or 921 earthquake) which was a M_W 7.6 event in September 1999 located just over 100 km to the northeast. The 1999 event resulted in over 2,400 fatalities and was the second deadliest earthquake in Taiwan history, after the 1935 earthquake just north of Taichung (Hsinchu-Taichung), which caused over 3,200 fatalities. A M_W 7.3 earthquake in December 1941, between the cities of Tainan and Chiayi (Zhongpu) and 55 km northwest of the Meinong earthquake, also caused several hundred fatalities.

Chi-Chi 1999

The M_W 7.6 Chi-Chi earthquake occurred on the 21 September 1999 in central Taiwan, approximately 30 km southeast of Taichung and 160 km southwest of Taipei, as shown in Figure 1. The magnitude of the Chi-Chi earthquake resulted in widespread damage which included 2,415 deaths, 11,000+ severely wounded, with 50,000+ buildings completely destroyed, 50,000+ buildings severely damaged, and a total of NT$300 billion (NZD$13.4 billion) worth of damage (http://www.nfa.gov.tw/). The impacts of the Chi-Chi earthquake have been widely reported, including a report from a NZSEE Learning from Earthquakes mission [1]. Extensive information and reports on the Chi-Chi earthquake can also be found on the EERI clearinghouse [6]. Examples of structural damage observed during the Chi-Chi earthquake are shown in Figure 2.

The Chi-Chi earthquake had a significant influence on earthquake engineering policy, practice, and society preparedness in Taiwan. Notable changes made to policy explored during this mission included the effectiveness of changes to design standards and seismic assessment and strengthening initiatives for older earthquake risk buildings, in particular schools and other public buildings.

---

[1] In 2009 Typhoon Morakot caused severe flooding, landslides, and debris flows, due to the extreme rainfall within a short period (2-3,000 mm within 48-72 hrs, accounting for almost 80% of the annual rainfall). 699 people were declared dead or missing, including nearly 500 people killed when the Shiao-lin Village was buried by landslides. This was the worst natural disaster in Taiwan since the 1999 Chi-Chi earthquake and had significant impact on Taiwan's disaster management system.

a) Bridge damage [7] *b) Building soft-storey collapse [8]* *c) School building damage [9]*

Figure 2: Damage during the 1999 Chi-Chi earthquake.

Kaohsiung Jiasian 2010

The M_w 6.4 Kaohsiung Jiasian earthquake occurred on the 4 March 2010. The earthquake was located to the northeast of Kaohsiung City with an epicentre approximately 24 km east of the Meinong earthquake. The earthquake was similar in magnitude to the Meinong earthquake, but slightly further away from Tainan, and as a result lower intensity ground motions were recorded. Structural damage was caused to a number of residential and school buildings, with two soft-storey buildings collapsing [10].

Design Standards and Initiatives Post-1999

Seismic design standards in Taiwan have developed over time based on both local and international practice. Modern design standards are similar to that in New Zealand relying on the principles of ductility and limit state design. The Taiwan design standards are heavily influenced by key international codes that are often adopted with local modifications.

Seismic hazard and design actions were previously adapted from the Uniform Building Code, and were more recently developed specifically for Taiwan with major revisions in 1997 and 2005 [11, 12]. Key revisions to the seismic design standard in Taiwan include:

- Prior to 1974: A nominal lateral load coefficient of 10% of the building weight was applied as a seismic load case.
- 1974: UBC introduced with three seismic zones across Taiwan. Determination of Base Shear incorporated the elements of seismic hazard, structural ductility, and natural period.
- 1982: Introduction of importance level factors based on occupancy level.
- 1989: Amendment to account for basin effects in the Taipei region.
- 1997: Major revision with the introduction of a response spectrum method and re-zoning of hazard into 4 regions. Based on a 10% probability of exceedance in 50 years.
- 1999 (post-Chi-Chi earthquake): Temporary re-zoning to increase the seismic hazard in the central region of Taiwan.
- 2005 (current version): Performance objectives based on a Design Earthquake (Life Safety), MCE Earthquake (Collapse Prevention), Serviceability Earthquake (Immediate Occupancy).
- 2011: Adjusting the number of seismic microzones within the Taipei basin region from four to three microzones. Amendments to earthquake designs.

The concrete design standards (土木401) have been based on the America Concrete Institute standards [13] since 1967. The 2011 version of the approved concrete design standard (土木401-100) is based on ACI 318-05 [14] with some modifications. More recently ACI 318-14 has been fully translated into both traditional and simplified Chinese for sale within Taiwan and mainland China [15].

Steel design standards in Taiwan are based on the American Institute of Steel Construction (AISC) standards.

The design of buildings is typically led by an architect who is responsible for coordination of the design consultants. Buildings for public use or taller than 4 storeys must be signed off by a registered civil or structural engineer, and buildings taller than 12 storeys must be signed off by a registered structural engineer. Plans are submitted to local district offices for approval, which in many cases only involves checking the documentation for compliance. Since the 1980s, buildings greater than 50 m high are required to undergo a peer review by a panel of independent experts consisting of university academics and/or members of the professional engineering society. As a result, many buildings are constructed slightly less than 50 m tall to avoid the peer review requirements. Despite being criticised following the Chi-Chi earthquake, these peer review requirements were not altered and remain as current policy.

The poor structural configuration of typical buildings was identified as a major issue following the Chi-Chi earthquake. The influence of “non-structural” infill and partition walls within concrete frame buildings resulted in a number of potential vulnerabilities, including soft-storeys and short (or captive) columns. This resulted in an increased awareness of the effect of partition walls. Following Chi-Chi, reinforced concrete frames with concrete partition walls and/or infill were still the most common structural form. However, there was a push to adopt more structural concrete wall buildings to reduce damage. Additionally, provisions for soft-storey designs were introduced. Buildings with soft-storeys, classified as those having a stiffness less than 70% of an adjacent storey or less than 80% of the average storey stiffness, are required to undergo dynamic analysis during the design. Buildings with extreme soft-storeys, classified as those having a stiffness less than 60% of an adjacent storey or less than 70% of the average storey stiffness, are no longer permitted.

Chi-Chi and other earthquakes also highlighted a number of poor detailing practices in concrete structures, such as inadequate transverse reinforcement in columns, deficient lap splices, absence of beam-column joint reinforcement, 90-degree bends for anchorage or stirrups and ties [8]. Many of these deficiencies had been non-compliant with the concrete design standards for some time, but had continued to be adopted in practice. Despite the presence of these modern design standards, poor quality construction and the lack of adequate construction supervision by engineers were highlighted as key issues.

Since the Chi-Chi earthquake there have been continued development and improvement to design standards. However, some of the changes lobbied for the building act legislation, such as increased construction supervision and review, were not implemented by the central government.

Seismic Evaluation and Remediation Initiatives Post-1999

During the Chi-Chi earthquake approximately 4,600 public buildings were damaged. In June 2000, the Taiwan Government established the "Building Seismic Assessment and Strengthening Programme", which required all public buildings that were built prior to May 1997 (27,740 buildings in total) to be assessed and strengthened where necessary. As of December 2015, 27,575 initial assessments (99.41%) and 13,843 detailed assessments had been undertaken. A total of 4,596 buildings had been strengthened, nearly 4,500 buildings were awaiting strengthening, nearly 2,000 buildings had been demolished, and nearly 1,500 buildings were awaiting demolition [16].

It was estimated that over 1.13 million private buildings were granted building use permits prior to May 1997, of which approximately 40% would not meet the requirements of current building standards. In 2007-2008, a draft Bill requiring seismic assessment and strengthening of existing buildings was developed. The Bill however was not passed because of its potentially significant impact and the lack of consensus between central and local government.

The Ministry of Education along with the National Centre for Research on Earthquake Engineering (NCREE) have also undertaken a seismic assessment and strengthening programme for school buildings in Taiwan. This programme was implemented to mitigate damage to vulnerable school buildings that was observed during the Chi-Chi earthquake and is discussed in detail in later sections.

In recent years, the programmes for evaluating and strengthening public buildings have become widely known, and the methodologies used and associated mechanisms have become familiar to the industry. Discussion of seismic assessment and strengthening has therefore extended to private buildings. However, most private buildings in Taiwan are multi-unit and multi-storey, and involve many different owners. As such, the evaluation and strengthening of such buildings often requires assistance from the government.

The Housing Act that came into effect in December 2012 and associated regulations include seismic evaluation as one of the key areas for residential building evaluations [17]. Amendments to urban renewal legislation over the last few years have also included processes and incentives for seismic assessments and remediation.

In 2015, the Taiwan Government launched a programme for seismic evaluation and remediation of private buildings [16]. This programme covers several aspects, including reviewing legislation; subsidising seismic assessments, strengthening, and rebuilds; developing strengthening methodologies; establishing an information system and register; and encouraging territorial authorities to undertake 'health checks' for residential buildings.

MEINONG EARTHQUAKE

The Meinong earthquake occurred at 3:57 am local time on Saturday 6 February 2016. The earthquake had a measured moment magnitude (M_w) of 6.4 and was centred at a depth of around 14.6 km [18, 19]. As shown in Figure 3 and Figure 4, the epicentre was in the Meinong District of Kaohsiung, approximately 40 km east of Tainan and 46 km northeast of Kaohsiung (epicentre co-ordinates were 22.92 N, 120.54 E). The earthquake occurred during the start of the Chinese New Year holiday when most people would have been travelling or gathering at home to celebrate.

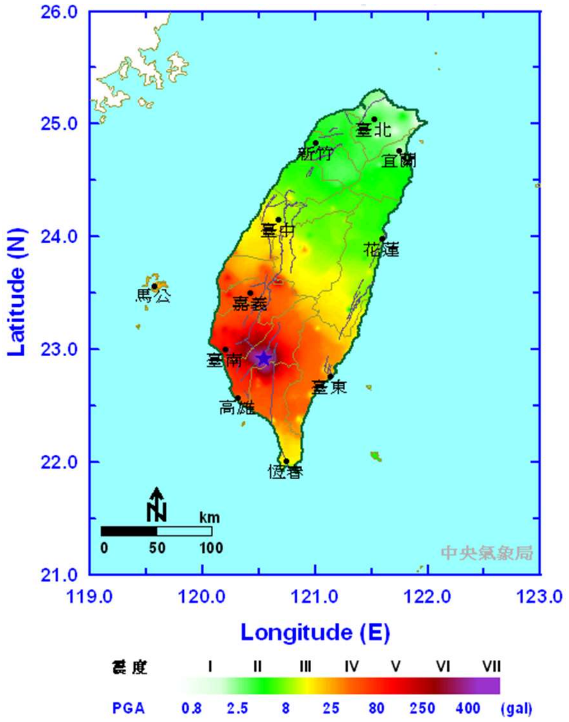


Figure 3: Meinong earthquake intensity map (Source: Central Weather Bureau, Taiwan).

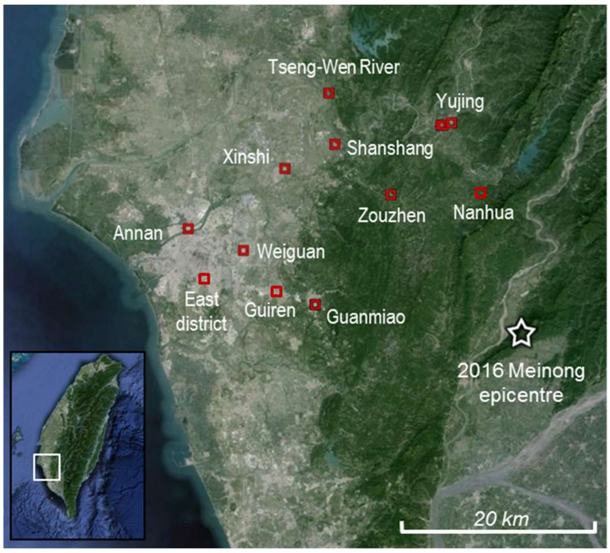


Figure 4: Meinong earthquake epicentre and visited sites (Google Maps).

The Meinong earthquake epicentre is shown in Figure 5 along with the mapped faults in the area. The earthquake occurred on a blind fault that was relatively young and not yet expressed at the ground surface. The focal mechanism to the main Meinong earthquake was characterised as strike-slip with an oblique thrust component. The source was complex, comprising two separate rupture sources. Analysis of the aftershock sequence shows two distinct clusters of aftershock sources and a rupture direction generally towards the west. A relatively large long period ground velocity pulse was also observed with some directivity effects. There was also evidence for a third "event" occurring at another potential source in the vicinity of Guanmiao, however further studies are underway to improve the understanding of the overall earthquake mechanism. Analysis of data indicates that the area in and around Tainan experienced higher PGAs and more consequential damage than elsewhere. However, there is no clear evidence to suggest amplification due to site effects. A stronger E-W component of shaking compared to the N-S component is evident from the strong motion data, particularly in the 0.5 s to 1.5 s range in Tainan. Records show a long period spectral peak at 0.7 s, regardless of site condition and epicentral distance, which may be associated with observed long period velocity pulse. Additional details of the earthquake local geology and seismology have been published by Clahan [4].

According to the CWB Real-time Seismic Monitoring Network, the largest recorded intensity was at station CHN3, located in Xinhua District 24 km from the epicentre, where a peak ground acceleration (PGA) of 0.40g was recorded in the E-W direction. The recorded ground motions and response spectra from the CHN3 station (120.40 N, 23.08 E) and the TAI station (120.21 N, 22.99 E) in downtown Tainan are plotted in Figure 6. The duration of the recorded ground motions was relatively short with significant shaking over 10-20 s. The shaking was generally more intense in the E-W direction with larger PGAs and spectral acceleration ordinates noted. The acceleration spectra generally exceeded the current design loads (475-year return period) and was close to the MCE demands (2500-year return period) for periods between 0.7-2.5 s. The shaking in Tainan was generally less than that of the closer towns, but still closely matched current design level earthquake demands for a period of 1.0 s. It should also be noted that the recorded intensities exceeded the design lateral loads specified in prior design standards, significantly so when compared to the low hazard used in the 1982 standard which would have been the basis of seismic design for much of the building stock.

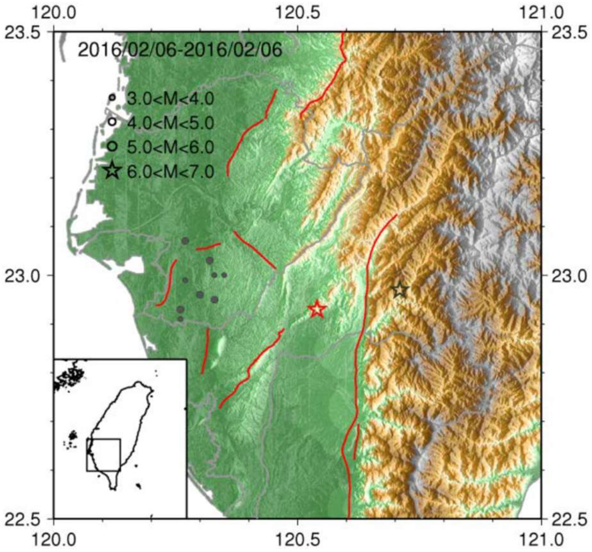
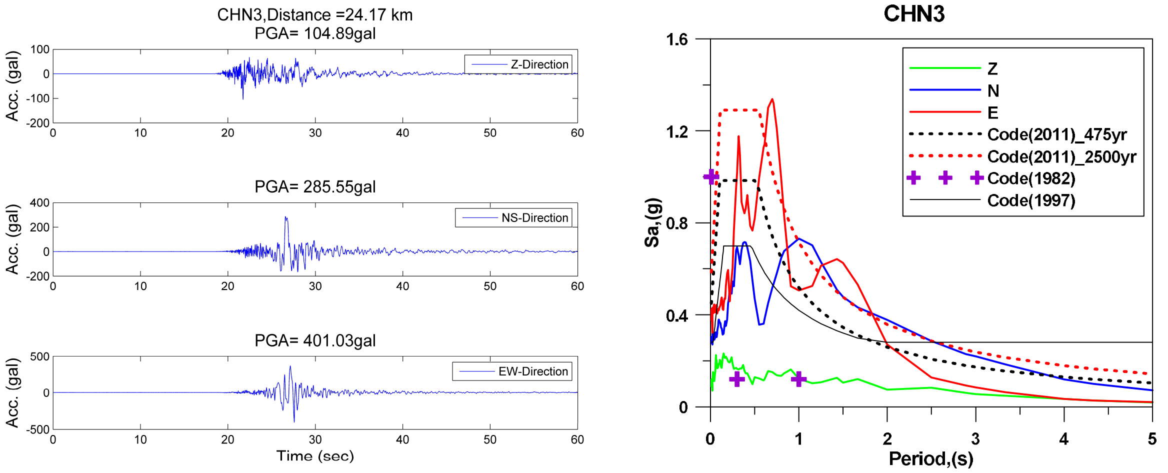
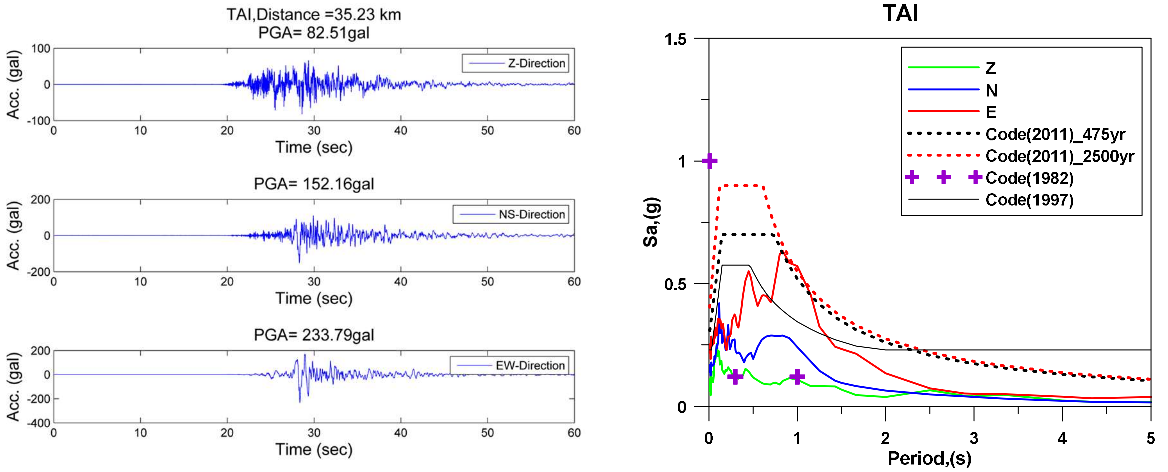


Figure 5: Mapped faults and epicentre (Source: NCREE).



a) CHN3 (Xinhua district)



b) TAI (downtown Tainan)

Figure 6: Recorded ground motions and response spectra (5% damping) (Source: NCREE and NCKU).

The worst affected city was Tainan, where a number of buildings collapsed or were severely damaged. Most of the casualties were concentrated in one building complex, the Weiguan Jinlong Building in the Yongkang District. There were 115 deaths and 96 injured, with close to 400 people rescued from the building. Total casualties from the earthquake on record were 117 deaths and 551 injured. Areas of major damage were spread around the greater Tainan area, in particular the districts to the north and west of the epicentre, as shown in Figure 4.

EMERGENCY RESPONSE

The timing of the Meinong earthquake on Saturday 6 February 2016 was two days before the Chinese New Year on 8 February, which is an important festival for all Taiwanese. Saturday 6 February marked the beginning of the nine-day long Chinese New Year holiday. The timing of the earthquake likely affected the social impacts and emergency response. The population of Tainan City and the occupants of the collapsed buildings were expected to be greater than normal as people would have travelled to southern Taiwan to prepare for the New Year family gatherings.

The Meinong earthquake occurred at 3:57 am and the National Central Emergency Operations Centre in Taipei was activated at approximately 4:15 am. This earthquake was seen as a local event and so the emergency response was managed by Tainan City Council with support from the central government. In total over 32,000 Urban Search and Rescue (USAR) personnel, firefighters, police, soldiers, and volunteers were involved in the operation (National Fire Agency website: www.nfa.gov.tw). The emergency operation was officially concluded 8 days after the earthquake on 14 February, which coincided with the end of the Chinese New Year holiday period.

Search and Rescue

Taiwan has advanced USAR teams that follow international protocols. During the Meinong earthquake over 2,000 search and rescue team members from 20 cities and counties throughout the country responded (Tainan City Council website: www.tainan.gov.tw). The search and rescue efforts were concentrated at the collapsed Weiguan Jinlong building. Due to the localised impact of the event, no international teams were called on to assist. A total of 14 residential properties near the Weiguan building were requisitioned by the Council for the use of emergency response centre, media centre, and offices for search and rescue teams. All of the 14 properties were returned to the owners after the recovery exercise in the Weiguan building was complete on 14 February. In total 115 people were killed in the collapsed Weiguan building, 95 people escaped by themselves, and 289 people were rescued by USAR teams. Despite the catastrophic collapse the large number of safely rescued residents was attributed to the way in which the building collapsed sideways with large sections of the building remaining intact.

Placarding and Barricading

Procedures for emergency building management are set out in the Disaster Prevention and Protection Act[2] (clauses 27 and 36), the Building Act (clause 81), and in the Post-Disaster Dangerous Buildings Emergency Evaluation Regulations[1]. Under those acts and regulations, those eligible to undertake emergency building evaluations include architects, civil engineers, structural engineers, and geotechnical engineers who are registered with local authorities for this purpose. Safety evaluations were organised and administered by the local districts in accordance with centrally published guidelines (Post-Disaster Dangerous Buildings Emergency Evaluation – Legislation and Procedures, 2009). The placarding procedures are similar to that in Japan and examples of the yellow and red placards are shown in Figure 7.

a) Yellow *b) Red*

Figure 7: Examples of placards.

The damage during the Meinong earthquake was generally isolated and so widespread rapid safety evaluations were not conducted. Instead the Tainan City Council worked with the four major professional societies – architects, civil engineers, structural engineers, and geotechnical engineers – to coordinate emergency building evaluations. This process relied on members of the public reporting concerns to the Council who would then liaise with the professional societies to coordinate the building evaluation. In total over 5,000 buildings were evaluated with 288 buildings given a 'red' placard (i.e. major structural damage) and 314 buildings given a 'yellow' placard (i.e. secondary structural damage such as ceilings or partitions, or threat from neighbouring property). A map of the placard distribution is shown in Figure 8. Placards were not given to the buildings that were assessed as suffering no or minor damage (i.e. no green/white inspected placards used). This process was similar to the residential placarding employed following the 2011 Christchurch earthquake and intended to avoid confusion when only a portion of buildings had been inspected.

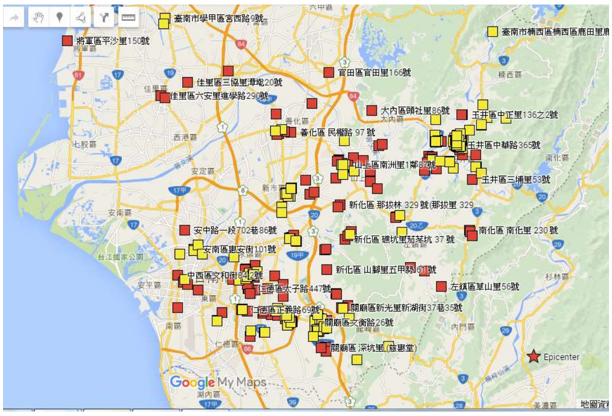


Figure 8: Map of red and yellow placard building (Source: NCREE).

The inspections and placards are intended to primarily focus on safety, but also have some implications to the extent of damage and reparability. Re-evaluation for buildings that were given a red or yellow placard commenced in March 2016. Building owners were required to contract experts from the four major

---

[2] The Disaster Prevention Act first came into force in 2000. Amendments to this act were made several times over last 15 years. The Post-Disaster Dangerous Buildings Emergency Evaluation Regulations came into force in 2009. The Building Act came into force in 1938 and was amended several times over the years.

professional societies to advise them on whether buildings with red/yellow placards could be repaired or should be demolished. The re-evaluation costs were covered by public donations to Tainan City Council. In addition, the Tainan City Council subsidised 50% of the building repair cost (up to NT$1m) or 50% of the demolition cost (up to NT$1.5m). For buildings that were demolished immediately after the earthquake, the Council provided different levels of subsidies. Owners of the demolished Weiguan building each received 100% subsidy (up to NT$3m). Owners of the demolished Xingfu building in Guiren and the Production Market in Tainan City each received 50% subsidy (up to NT$1.5m). Those subsidies came from public donations. Owners of the apartment complex in Wen-Ho St. did not receive any subsidy from the Council as they had received a NT$10m donation from the real estate development association.

Several buildings with red placards visited were still occupied, such as that shown in Figure 9. This may have been due to the damaged buildings having already been temporarily stabilised and the placard not being updated or removed. However, this may also indicate a lack of alternative accommodation provided to relocate residents of damaged apartment buildings. For typical mixed-use buildings, a single title is often both the family business (ground floor) and residence (upper floors). Occupants are therefore less likely to relocate at the risk of losing both their home and business and may be willing to tolerate a higher level of risk by remaining in the damaged building.

Figure 9: Occupied red placard building.

The use of barricading around damaged buildings was not widespread. The lack of barricading observed may have reflected the quick recovery and demolition or stabilisation of severely damaged building. However, a number of red placard buildings visited had either no or poor barricading despite being a potential collapse risk. The red placard building shown in Figure 10a had severely damaged columns on the front of the ground floor and although temporary props had been installed, no barricading was in place. Another district office building, shown in Figure 10b, had severely damaged columns at the front of the building and hazard tape had been placed around the entire building. No temporary stabilisation had been installed in this district office and the taped area would not have provided adequate protection if the building did collapse during an aftershock.

a) Lack of barricading around a red placard building

b) Hazard tape surrounding severely damaged building

Figure 10: Examples of barricading.

As in New Zealand, there appears to be a need for increased education and communication with the public to ensure that the building safety evaluation process and placards are understood. Additional education of engineers and district officials administering this process would help to increase the consistency of the post-earthquake evaluations, placarding, and barricading.

LAND AND LIQUEFACTION DAMAGE

Land damage due to the Meinong earthquake was generally localised and relatively modest, which is not unexpected given the relatively modest level of ground shaking associated with this event. Within lowland areas potentially susceptible to liquefaction the recorded free-field PGAs were typically of the order of 0.2 to 0.25 g, or less. This is roughly equivalent to Christchurch Serviceability Limit State-level shaking.

Sparodic localised sand boils were observed in open ground within the lowland district of Xinhua, which is located approximately 4 km to the south of Xinshi, refer to Figure 11. These are also visible on Google Earth with photography date of 7th February 2016.

Slope failure also occurred as a result of this earthquake at the Nanbao golf course, as shown in Figure 12. At this site the slide mass moved in a relatively coherent manner towards a creek bank with relatively low level translational movement in more of a rotational failure mode.

The site of three lateral spreading-related slope failures within the Rixin Levee on the Tseng-Wen River is shown in Figure 13. At the time the team visited, initial repairs had been completed for the area immediately adjacent to the Freeway bridge abutment (Failure #1) and were well underway for the middle area (Failure #2). No specific damage to the bridge structure has been reported.

Figure 11: Xinhua sand boils (GEER [20])

Figure 12: Slope failure at Nanbao golf course (Source: NCREE).

a) Overall view (Source: Google Earth)

b) Location (red star indicates earthquake epicentre)

c) Failure #3

d) Failure #2

e) Repair of failure #2

Figure 13: Tseng-Wen River levee failures.

The slope instability of the Rixin Levee is considered to result from a particular saturated cohesionless fill layer at or below the base of the levee that liquefied during the earthquake, resulting in slope failure and lateral soil displacement (runout) of between approximately 30 m and 135 m. The fill is presumed to directly overlie a naturally occurring low permeability silty clay soil, which was identified in soil investigations associated with a pipeline bridge located approximately 500 m downstream from the adjacent Freeway bridge. Discussions with a local engineer indicated that there was most likely no subsurface investigation information associated with the levee (or its repair) away from any bridge structures. It is also understood that piles have been placed beneath the levee immediately adjacent to the upstream side of the right bridge abutment and opposite the factory structure visible in Figure 13. No instability was observed within this part of the levee. Some ground surface settlement of the order of 100 mm and surface cracking was observed adjacent to the bridge pier on the right abutment of the Freeway bridge at an elevation coincident with the top of the river levee, as shown in Figure 14.

Liquefaction-related ground damage was also observed associated with the concrete-faced levee on the true right river bank approximately 11 km upstream from the Freeway bridge shown in Figure 14. At this upstream location some relatively modest vertical and lateral ground movement occurred at the site of a previous levee repair and was characterised by cracking and damage to the concrete facing, surface ejecta on the ground surface within a plot of land immediately behind the levee crest and ground cracking at the levee crest. The magnitude of ground displacement appears to have been of the order of 0.3 m.

Figure 14: Ground surface settlement and crack adjacent to Freeway bridge pier on the right abutment.

Liquefaction-related ground surface subsidence with associated ground surface cracking was observed in a limited number of residential areas in and around Tainan City. This occurred in localised areas associated with backfilling of historical fish farming ponds. Backfilling is reported to have occurred in the 1970s and 1980s using a variety of materials and it is presumed that construction practices were somewhat rudimentary and the filling occurred in a non-engineered manner. Liquefaction-related damage included settlement and tilting of buildings, which predominantly comprised 2 to 5 storey residential reinforced concrete framed buildings. The foundations for the vast majority of these buildings were typically reinforced concrete ground beams with unreinforced slab-on-grade infill floors at ground level. The groundwater table is typically relatively shallow and may vary between approximately 1.0 to 2.0 m below ground level. The photos in Figure 15 show examples of this type of earthquake damage. Earthquake-related building damage other than that due to mainly liquefaction is described in the following section.

The photos within Figure 15 illustrate several points, including the relatively uniform settlement of the main residential building. In this case there is little tilting of the overall structure indicating that the foundation essentially punched into the underlying soil vertically. The settlement of the foundation ground beams, which are carrying the building loads, has resulted in the hogging of the ground floor slab. At the time of the NZSEE visit there was very little liquefaction ejecta evident either on the ground surface around the building or within the structure. Observations from other photographs taken in the area within two weeks of the earthquake, Google Earth imagery dated 7 Feb 2016 and discussions with local engineers indicated that there was relatively limited ejecta expressed at the ground surface during this event. Discussion with a local engineer indicated that the majority of liquefaction-related ground investigation is conducted using borehole drilling with Standard Penetration Tests (SPTs) and shear wave measurements (refer Figure 16 below). It is worth noting that the critical layer(s) identified on the right hand plot in Figure 16 have a low cyclic resistance ratio (CRR) calculated using the estimated earthquake parameters and the site investigation data. These layers have a corresponding calculated factor of safety against liquefaction less than 1, and are expected to have liquefied during the earthquake.

Figure 17 provides an example of liquefaction-related land damage and associated residential building damage. In this case, which is located in the Annan District and again associated with historical backfilling of a former fish pond, the building has punched and tilted as a result of liquefaction of the underlying soil. Vertical settlement is of the order of 1.0-1.2 m and the building has tilted by approximately 8 degrees. The building superstructure appeared to have held together well despite the obvious foundation movement. Figure 17b shows a liquefaction ejecta-filled drainage trench immediately adjacent to the building.

a) Damaged ancillary buildings (GEER [20])

b) Site following demolition of damaged ancillary buildings

c) Hogging of the unreinforced floor slab within dwelling

d) Damaged ground slab in front of dwelling (GEER [20])

Figure 15: Liquefaction-related damage to residential building in the Xinshi District.

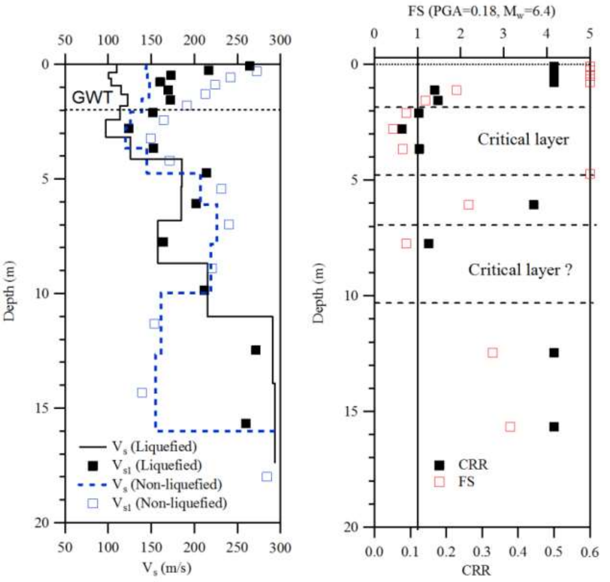


Figure 16: Vs profiles and liquefaction analysis for Xinshi site (GEER [20]).

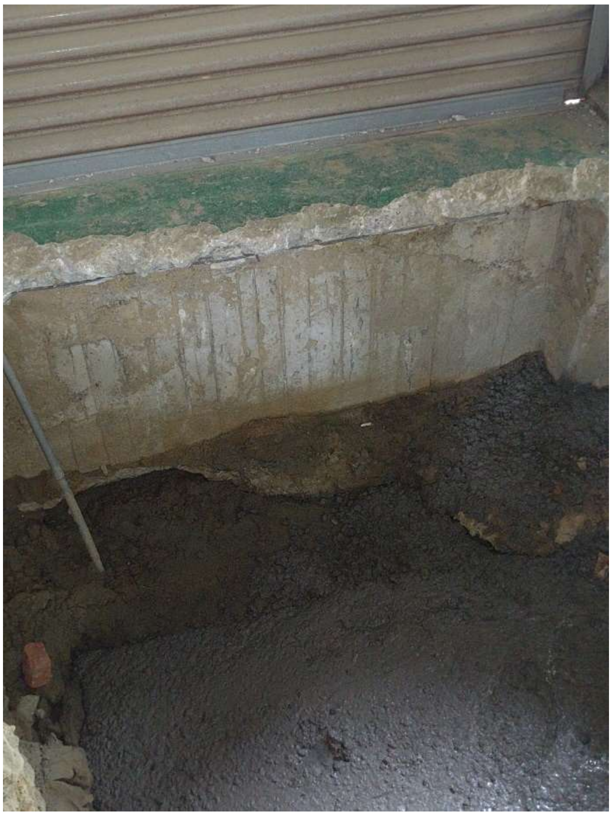
At the time of the NZSEE team visit a building in this area was undergoing repair involving jacking and re-levelling of the foundations. The photos in Figure 18 show the building and the nature of the foundation ground beams that had been exposed to enable positioning of the jacks. The perimeter foundation beams (Figure 18c) are approximately 0.8 m deep and 0.4 m wide. Dewatering was also carried out to facilitate the repairs and the plastic pipework is evident (Figure 18b). The unreinforced slab-on-grade floor is clearly shown along with nominal tie bars between the slab and the ground beams. At the time of the team visit the re-levelling had just been completed. Discussion with the owner indicated that the building had settled approximately 150 mm, although this was an estimate as no measurements were believed to have been taken of building settlement or tilt.

a) Tilted residential building

b) Drainage trench

Figure 17: Liquefaction-related damage to residential building in the Annan District.

a) Overall building (Source: Google Earth)



b) Pipework for dewatering

c) Perimeter foundation beams

Figure 18: Building undergoing foundation repair.

BUILDING DAMAGE

The distribution of buildings in Tainan is shown in Figure 19 for age, construction material, and storey height. The majority of buildings were constructed since 1983, with 43% constructed between 1983 and 1997. Building typology in Taiwan is representative of the design for multiple hazards due to the risk of both large earthquakes and regular typhoons. As a result, the majority of buildings (65%) are constructed from reinforced concrete (RC) or concrete masonry (CM). Tainan is considered a small city when compared to Taipei or Kaohsiung, and as a result is predominantly constructed from 2-7 storey buildings. High rise buildings have been built more recently in small pockets around Tainan city, but only equate to 1% of the building stock.

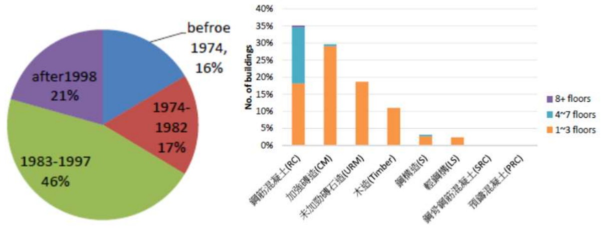


Figure 19: Distribution of buildings in Tainan by age, construction material, and storey height (Source: NCREE [20]).

The most common form of construction consists of reinforced concrete frames with either masonry or concrete infill. In older buildings the infill typically consists of unreinforced masonry (URM) using bricks that are 120×240×60 mm to create walls that are either 120 or 240 mm thick (240 mm is most common). In newer buildings constructed in the last 10-20 years, the infill is typically reinforced concrete that is either 150 mm or 250 mm thick (150 mm is most common). These heavy partition walls are not considered as structural components and the design of the building is based on an analysis of the bare reinforced concrete frame. However, the infill is not isolated from the frame and so is expected to influence the lateral strength and stiffness of the building considerably.

The damage to buildings during the Meinong earthquake was isolated to a small number of buildings, with the majority of building stock preforming adequately. Media reports focused on several high profile buildings that collapsed, including the Weiguan building where 115 people were killed and other residential buildings and markets where people were lucky to escape without loss of life. However, as shown by the placard data in Figure 8, building damage was more widespread than initially reported.

When the NZSEE team arrived more than a month after the earthquake, Tainan appeared to have recovered quickly with people going about their lives as before and minimal visible examples of damaged buildings. Upon closer inspection a number of smaller regions or districts had concentrations of damaged buildings that had not yet been repaired or demolished. These clusters of damage in districts to the immediate north and west of the epicentre (Guiren, Guanmiao, Nanhua, Shanshang, Xinhua, Yujing) where relatively high PGAs were recorded. Perception of the speed of recovery may have been influenced by the lack of barricading and the fact the many residents were still living in severely damaged buildings that were awaiting repair.

The observed performance and typical damage to different types of buildings is described below, focusing on mixed-use buildings, multi-unit residential buildings, core wall buildings, modern apartment buildings, markets, URM houses, and schools.

Mixed-Use Buildings

The most common type of construction within the urban areas of Tainan and district town centres are 3-6 storey mixed-use buildings, such as the examples shown in Figure 20. The ground level is used for commercial or light industrial shops with residential units in the upper levels. This configuration provides both a business and accommodation for the family, often incorporating a number of generations under the same roof. The term used to describe this traditional construction roughly translates to “through to the sky”, where a family will own the unit from ground floor to the roof. The buildings are typically constructed from reinforced concrete frames with either unreinforced masonry or reinforced concrete infill walls. Some of these mixed-use units were constructed together in rows or group, whereas others are individual buildings that are constructed with no separation between each other.

There is no publicly owned verge or footpath on many Taiwanese roads, and instead laws require that a pedestrian thoroughfare be provided at the front of property adjacent to roads. As shown in Figure 20, this often leads to the upper levels of the building being built above a covered footpath to maximise land use. In combination with the use of heavy infill and partition walls, this configuration can result in a potential soft-storey that would not typically be considered when designing the structure as a bare reinforced concrete frame. Where buildings are located on a corner, significant torsional issues can combine with the soft-storey configuration to compound the likely poor building performance in an earthquake.

Despite the poor structural configuration, these mixed-use buildings typically performed well during the Meinong earthquake with minimal damage observed to the majority of these buildings. Damage was typically cosmetic and was likely to be repaired by the owner with no engineering input. It was considered that the increased strength and stiffness of the infill walls generally provided sufficient lateral load capacity to resist the demands imparted. Damage to a 3 storey building is shown in Figure 21 where a column at the front of the building was crushed and the floor slab was hogging due to punching of the foundation beam. There was no evidence of liquefaction at this site.

Despite being open on the ground floor with few walls for stiffness, particularly at the front of the building, the close proximity of these buildings to each other appeared to have provided increased strength. However, the poor structural configuration and potential soft-storey is likely to lead to non-ductile behaviour when subjected to an earthquake of sufficient intensity to exceed the buildings capacity. For this reason, these buildings are still considered an earthquake risk and further work is essential to mitigate the risk posed by this large portion of the building stock.

a) Row of 3-4 storey buildings

b) Isolated buildings

c) Modern reinforced concrete frame with infill

d) Original 2 storey building with additional floor

Figure 20: Typical mixed-use buildings.

a) Overall building

b) Damaged column

c) Hogging of floor slab

Figure 21: Damaged 3 storey mixed-use building.

Typical mixed-use buildings are not considered engineered buildings and often have additional storeys or rooms added as the family grows. These building additions are usually not consented and are often located towards the rear of the building to provide a roof garden, and as such are not always visible at street level. Many of these additional storeys are constructed from light-weight construction (referred to as an 'iron sheet house'), as shown in Figure 20d, but others are constructed from reinforced concrete or unreinforced masonry. The weight from these heavy additional storeys may lead to overloaded columns. The building shown in Figure 22 appeared to be four storeys from the front, but was actually six storeys at the rear. The building addition at the rear of the building was not original and the increased weight may have contributed to the damaged observed in a central column that had steep inclined cracking characteristic of an axial-shear type failure.

a) Front (4 storeys) ***b) Rear (6 storeys)***

Figure 22: Added storeys on top of building.

Multi-Unit Residential Blocks

Larger residential buildings consist of 5-16 storey buildings with multiple apartment units. These buildings are similar to the lower height mixed-use buildings, constructed from reinforced concrete frames with infill, having an open ground floor for shops and a covered footpath at the front. Compared to the lower height mixed-use buildings, more severe damage was observed in these taller residential buildings. In almost all cases this damage concentrated in the columns in the lower storey of the building. Several examples of this type of building either fully or partially collapsed during the earthquake, and a number of others were close to collapse. In particular, a number of the collapsed buildings were located on a corner where significant torsional issues combined with the soft-storey configuration. Some of the collapsed buildings are described below in addition to those with severe column damage that narrowly avoided a similar outcome. Additional information and photos of the collapsed buildings have been published by NCREE [21] and Tu [22].

Weiguan Jinlong Building

The building was a predominately residential building, with commercial use in the lower floors. Located in Yongkang District northeast of central Tainan and constructed in 1994. As shown in Figure 23a, it had 16 storeys and one basement and was constructed of reinforced concrete frames with some short reinforced concrete walls. The structure on the upper levels was transferred to several large columns on the ground level to allow open plan space for shops. The building collapsed catastrophically, overturning and falling across the road to the east side of the building, as shown in Figure 23b. In addition to being designed in accordance with older seismic design standards, the building contained significant irregularities in both plan and elevation. Initial reconnaissance teams observed possible failure of reinforcing bar couplers in the lower storeys and poor seismic detailing of transverse and longitudinal reinforcement [22]. Preliminary information from field investigation borehole logs indicates that liquefaction was not expected at the site, with the soil profile comprised predominantly of interlayered soft to firm silty clay (non-liquefiable) and loose to medium dense silty fine sand (potentially liquefiable), with the groundwater level at approximately 2.0-2.5 m depth. Relatively thin layers of liquefiable material may have been present at or close to the footing level at some locations, although no observations of liquefaction ejecta at the ground surface were reported. The bearing capacity of the soils within the upper 4-5 m appears to be relatively modest and some localised plastic soil deformation adjacent to more heavily loaded footing elements could have been expected.

King's Town Bank

As shown in Figure 23c, King's Town Bank was a 12-storey reinforced concrete building in the Xinhua district, northeast of central Tainan, that was constructed in 1996. The lower two storeys were occupied by the bank and the upper storeys were being converted to a hotel and so the building was unoccupied at the time of the earthquake. The building collapsed with the lower four storeys being crushed during the earthquake, as shown in Figure 23d. The building was on a precarious lean and was demolished quickly to avoid the risk of further collapse and the fact that a petrol station was located across the street.

Lane 101, Taizi Road

Another collapsed building had three reinforced concrete storeys and an additional storey constructed of lightweight materials, as shown in Figure 23e. The building was located in the Rende District, east of central Tainan, and was constructed in 1980. The ground storey of the building collapsed during the earthquake, as shown in Figure 23f. The building was of low strength by current design standards, and also had a symmetrical torsional irregularity due to the corner location and a ground floor soft-storey.

Xingfu Building

The Xingfu (or Happiness) building was a 7-storey apartment building located in Guiren District, southeast of central Tainan and was constructed in approximately 1992, as shown in Figure 23g. The bottom two storeys were designated for commercial use and the upper storeys were residential. It was located on the corner of a street intersection. The building had a significant failure with the bottom three storeys collapsing, while the upper levels remained almost intact, as shown in Figure 23h. The form of the structure is of typical construction with reinforced concrete frames through the building, with the residential levels having a large number of reinforced concrete infill and partition walls. It is suspected that this structural configuration combined with added torsional eccentricities due to the corner location contributed to excessive demands on the soft ground storey of the building.

a) Weiguan Building - Before (Source: Google maps) *b) Weiguan Building - After (Source: www.udn.com.tw)*

c) King's Town Bank - Before (Source: Google maps) *d) King's Town Bank – After (Source: Prof. Y-H Tu)* *e) Taizi Road - Before (Source: Google maps)* *f) Taizi Road – After (Source: Prof. Y-H Tu)*

g) Xinfu Building - Before (Source: Google maps) *h) Xinfu Building – After (Source: Prof. Y-H Tu)*

Figure 23: Collapsed apartment buildings.

Severe Column Damage

A number of other buildings similar in typology to the collapsed buildings were also observed to have severely damaged columns on the ground storey. In many cases the columns did not appear to have much residual capacity and the buildings were considered to have come close to collapse.

The 5-storey building shown in Figure 24 was located in Guiren District, southeast of central Tainan and was constructed in approximately 1992. The columns on the side of the building adjacent to the street were all severely damaged with significant cover loss, inclined shear cracks, and crushed core concrete. Temporary props had been added to provide gravity load support and the building had a red placard, although occupants were still living in the building. In addition to the structural configuration resulting in large demands on these columns, poor seismic detailing was observed in the columns, as shown in Figure 25. Identified detailing deficiencies included:

- Lap splices of all of the longitudinal reinforcement at the base of the column resulting in a weak section above (similar to short column effect).
- Widely spaced transverse reinforcement.
- 90-degree anchors in stirrups opened up at the corners.
- Fractured stirrups (possibly due to bending quenched and tempered steel).
- Large concrete cover depth (~100 mm).
- Electrical boxes embedded in the front of columns.
- Rainwater downpipes located within the column core.

a) Overall building

b) Column damage

Figure 24: Column damage in 5-storey building.

a) 90deg stirrup bend *b) Fractured stirrup*

c) Electricity box, large cover, stirrup spacing *d) Downpipe, large cover, stirrup spacing*

Figure 25: Poor column detailing.

Another example of similar column damage was observed in the building shown in Figure 26. The building was built in 1989, originally a five and a half storey building, but over the years another storey had been added on top. As with the previous building, the columns on the street front of the building were all damaged with axial/shear type failures. The building had a red placard, but still had families living in the block. As shown in Figure 26c, a number of the deficiencies listed above were again identified and in this case the column appeared to be missing some of the stirrups. Additionally, the additional seismic mass of the added storey and the poor seismic resistance on the ground floor would have contributed to the observed column damage.

a) Overall building

b) Propped columns *c) Damaged column*

Figure 26: Column damage in 5+ storey building.

Infill Panel Damage

Despite the use of infill being widespread, only limited damage was observed to the infill panels. The strength and stiffness provided by the infill appeared to prevent significant deformation demands. In addition, the infill was generally thick enough to avoid typical damage such as diagonal panel cracking, compression strut failure, or out-of-plane failures.

Some examples of observed infill panel damage are shown in Figure 27. Diagonal cracking of concrete infill panels is shown in Figure 27a and b, whereas Figure 27c and d show damage to columns and beams caused by the restraint provided by the infill panels. Damage to the primary structure from the infill systems is obviously much more of a concern and can require significant intervention to repair the damage. Column damage due to half height partition walls (short column effect) was also observed in many school buildings and district office buildings, as discussed in later sections.

a) Cracking in internal reinforced concrete infill wall

c) Column damage (Source: Prof. Y-H Tu)

b) Infill wall damage (Source: Prof. Y-H Tu)

d) Beam damage due to infill

Figure 27: Infill wall damage.

Core Wall Buildings

Although not common in Taiwan, there was one example of a reinforced concrete core wall building. The building, shown in Figure 28, was built in 1994 and consisted of an 11 storey tower above two storeys of basement parking. The reinforced concrete core wall was centrally located in the building plan with gravity load resisting columns around the perimeter of the building. The walls were between 500-660 mm thick at the base and heavily reinforced with up to 39 × 32 mm longitudinal bars at the ends of the walls equating to a 3.2% reinforcing content. Coupling beams in the core wall contained a diagonal reinforcing arrangement, consistent with New Zealand and North American practice.

The core wall was relatively undamaged during the earthquake with only minor cracks observed. Minor diagonal cracking and cracking at the ends of the coupling beams was also observed up the height of the building, as shown in Figure 28e. However, the columns on the perimeter of the building did not perform well, and two columns were severely damaged, one in the basement (Figure 28c) and one at the ground floor (Figure 28d). In both cases the columns attracted high axial loads with large beam spans and had widely spaced transverse reinforcement at 400 mm spacing. Additionally, despite the drawings showing 135-degree hooks on all stirrups and ties, the damaged columns clearly showed that 90-degree hooks had been used during construction and these had opened up. Damage to the column in the basement was concentrated above a splice in the longitudinal reinforcement and the severe buckling of the reinforcement indicated that a significant tension demand must have been induced prior to the column failing in compression. The column at the ground floor indicates that no transverse reinforcement was placed in the beam-column joint region and that the longitudinal bars had buckled outwards as a result.

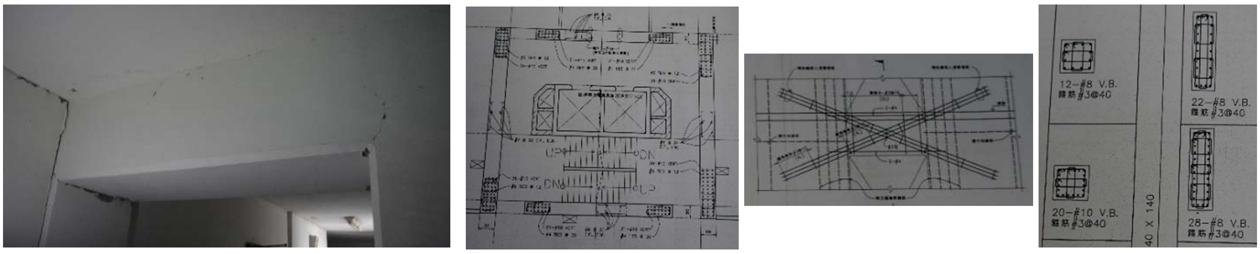
The building had been given a yellow placard and was in the process of being repaired when team members visited. The proposed repair consisted of installation of steel columns either side of the damaged column in the basement. The repair strategy had been proposed by an engineer and requires approval from the local district council.

a) Front view of damage tower

b) Rear view of damage tower

c) Basement column

d) Ground level column



e) Coupling beams

f) Drawings of core wall, coupling beams, and columns

Figure 28: Core wall 11 storey apartment building.

Modern Apartment Buildings

In recent years, an increasing number of taller apartment buildings have started to be constructed in Tainan, with large concentrations in the East District. Two such examples are shown in Figure 29, consisting of an 18 storey building constructed in 2012 and a block of 13 storey buildings of similar age. These buildings represent more modern building configurations with a greater awareness to potential soft-storeys effects. The buildings rely on a regular arrangement of reinforced concrete frames in combination with several reinforced concrete walls that extend up the full height of the building. Heavy infill partition walls and cladding elements are still used in the upper levels with an open plan foyer area on the ground floor. This configuration appears to have worked well with no visible damage to either of the buildings shown in Figure 29. High PGAs and damaged building were observed in the East District where these building were located, and so this provides some evidence that modern (post-Chi-Chi earthquake) building designs have improved.

Nearby to the building described above was a block of 14 storey apartments built in 1998 and shown in Figure 30. The four towers were constructed above a single basement carpark with the weight of the upper storeys being transferred to columns with large spans up to 12 m. There was visible distress to the columns and infill walls at ground level, such as that shown at the corner column in Figure 30b. In the basement there was diagonal cracking in most of the reinforced concrete walls (Figure 30e), but most of the columns were not significantly damaged with the exception of one. The column under one of the corners of the building above was severely damaged with axial-shear failure along a 45-degree plane, as shown in Figure 30c. Despite closely spaced stirrups and ties (~120 mm centres), the 90-degree hooks in the stirrups and ties had opened up and a number of stirrups had fractured as well (Figure 30d).

a) 18 storey building circa 2012

b) 13 storey block

Figure 29: Undamaged modern apartment buildings.

a) Block of four buildings

b) Corner at corner of ground level

c) Damaged column in basement

d) Poor reinforcement detailing

e) Diagonal cracking in wall

Figure 30: Severely damaged 14 storey apartment complex.

Markets

Markets in Taiwan also represent a significant earthquake-prone structural configuration. The markets typically consist of heavy upper levels stiffened by infill walls above an open plan market place with slender columns and few walls. This configuration creates a severe stiffness discontinuity and soft-storey at the ground floor. The risk is increased due to the high occupancy of the markets during busy hours of the day.

The old market in Nanhua (north of the epicentre) shown in Figure 31 is an example of a common local market with open plan ground floor with a heavy box like structure above. This market was damaged during the 2010 Kaohsiung Jiasian earthquake and subsequently strengthened with the installation of steel columns on either side of damage columns (Figure 31c). The market was subsequently closed in 2014. The ends of the columns sustained fresh damage during the Meinong earthquake, but the building did not collapse.

a) Overall building

b) Column damage ***c) Column with steel supports***

Figure 31: Column damage at Nanhua old market

Two other markets in Tachi and Shanshang did collapse during the earthquakes and these are shown in Figure 32. Fortunately, the timing of the earthquake in the early hours of the morning meant that the market was empty and so no one was killed in these buildings. Residents in the upper stories that remained intact when the ground level collapsed were able to escape with minor injuries.

a) Tachi market

b) Shanshang market

Figure 32: Collapsed markets (Source: Prof. Y-H Tu).

URM and Adobe Houses

Older districts still contained small areas of traditional URM and adobe house construction. The buildings of this type are less common as many of the inhabitants have moved into more modern buildings. Figure 33 shows some of the observed damage to URM and adobe houses in an area of Guanmiao district. Some of these buildings performed poorly with walls failing and roofs falling in. However, many were relatively undamaged and were still occupied.

School Buildings

The Chi-Chi earthquake in 1999 caused significant damage and collapse to a number of school buildings. School buildings in Taiwan are typically multi-storey and of non-ductile reinforced concrete construction. One of the school sites with buildings that collapsed dramatically is now the site of the 921 Earthquake Museum of Taiwan, a national museum on seismology and earthquake awareness. A large seismic assessment and retrofit programme was initiated following Chi-Chi which is described in detail in later sections.

In total, 469 schools suffered damage during the Meinong earthquake, including 195 schools in Tainan, 96 schools in Kaohsiung, 37 schools in Chia-Yi (north of Tainan), and the rest in the surrounding regions [23]. The total losses were estimated at NT$0.27b.

Some examples of damaged school buildings in the Meinong earthquake are presented below that include both existing and retrofitted buildings.

a) Damaged adobe and URM house

b) Collapsed URM house

c) Repaired roof that collapsed

Figure 33: Damaged URM houses.

Yujing Junior High

The Yujing Junior High School classroom block shown in Figure 34 is a three storey reinforced concrete building that was built in 1998 and had not been seismically retrofitted. The lateral load resistance in the long direction of the building is provided by reinforced concrete frames, but the impact of the reinforced concrete infill walls has not been fully considered. The front support columns are short columns, or "captive columns" as described in Taiwan. A downstand spandrel and an upstand concrete sill have restrained the column deformation resulting in a short column effect and shear failure, as shown in Figure 34b. The cantilevered front face of the building has also induced demands that damaged a feature wall with a circular hole. Non-structural damage consisted of a large area of ceiling tiles falling.

a) Classroom block

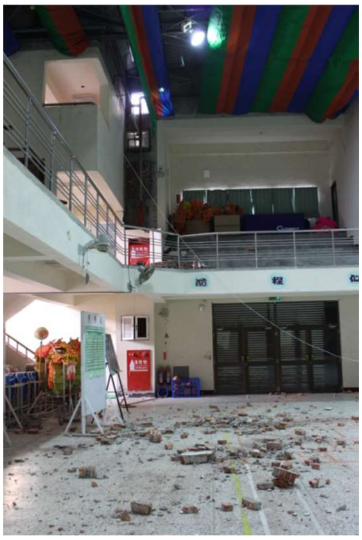
b) Damaged column

Figure 34: Yujing Junior High Classroom (NCREE [21]).

The Yujing Junior High School Activity Centre was built in 1997 and is a reinforced concrete building of significant height with corridors alongside one side of the building. As shown in Figure 35, there was significant damage to the masonry veneer and debris fell on the inside of the building. There was also damage to the irregular beam column frames which provide lateral resistance and support the brick facades. These did not collapse but had significant damage at the location of stiffness transitions in the frame.

Yujing Elementary

While the buildings at this school were not particularly badly damaged, the actual damage reflected the critical structural weaknesses that have been commonly identified in New Zealand buildings. These include the damage to short columns from having bound-in secondary structure, damage from pounding with insufficient seismic gap, and stiffness irregularity, both vertical and horizontal. Figure 36a shows a typical short column shear failure, and Figure 36b shows a storey mechanism where the support beams have shear cracking due to not fully considering the effect of the infill secondary structure inside the beam column frames. The school also experienced non-structural damage, which included falling ceiling tiles, fans, and lighting.



a) Falling bricks inside

b) Damaged wall

Figure 35 - Yujing Junior High Activity Centre (NCREE [21])

a) Damaged short column

b) Shear crack in support beams

Figure 36: Yujing Elementary School.

Guiren Junior High

Guiren Junior High School presents an excellent case study on the impacts of the Meinong earthquake on a set of school buildings. The school has been part of the nationwide seismic retrofit programme and most of the retrofit work planned had been completed, but there were two buildings that had not been retrofitted at the time of the earthquake. As shown in Figure 37, these two existing buildings (of nine in total) suffered the typical damage seen in other buildings, including damage from short columns, pounding, and damage due to stiffness irregularity, particularly vertical stiffness issues.

a) Damaged column

b) Building pounding

Figure 37: Guiren Junior High.

Figure 38 shows a photo of a school building that was strengthening prior to the Meinong earthquake. The strengthening work included the addition of a new moment frame adjacent to the original structure. This building did not suffer any visible earthquake damage.

Figure 38: School building strengthened by the addition of a supplementary moment frame.

Non-Structural Damage

A reasonable amount of non-structural damage was observed to school buildings. The typical failures involved ceiling tiles and mechanical equipment and ducting in the classrooms, halls and administration buildings, as shown in Figure 39 and Figure 40. Non-structural damage to school buildings was investigated during post-earthquake reconnaissance [24]. Of interest were the stainless steel water containers that are common all over Taiwan as a means of emergency preparedness. They are of a typical make and form and the tank legs typically failed, resulting in overturning of the tanks, as shown in Figure 41. In some instances, the tanks did not overturn, but failed through punching of the supports into the tanks.

Figure 39: Mechanical ducting support failure (Source: NCREE).

Figure 40: Ceiling tile failure (Source: NCREE).

Figure 41: Typical water tanks that were damaged during the earthquake.

Foundation Performance

In general, little foundation damage was observed at the sites visited by the team. Even in cases where substantial building settlement and tilting occurred, which was due to liquefaction within the underlying soils, the shallow footings (ground beams) appear to have performed well and not contributed to structural failure. Non-structural floor slabs suffered significant damage, but these are generally able to be readily replaced. Even in the absence of liquefaction localised foundation punching was observed (refer Figure 21), which is expected to be related to plastic yielding of the soil at the footing level from localised soil-structure interaction under seismic loading.

LIFELINES AND BRIDGE DAMAGE

Overall, the disruption to lifelines during the Meinong earthquake was relatively modest and most services were restored within a short period. Reports of damage to bridges and lifelines have been published by NCREE [21], and NCDR & NCREE [24], and key findings included:

- Service interruptions associated with major roadways included temporary outages or restrictions at:
    - Provincial Highway No. 3, Dongshipu road bridge (near Neiman Elementary School - approximately 8 km west of the Meinong epicentre). Settlement of one of the bridge piers by 100-150 mm required temporary road closure for repairs. The bridge was re-opened with speed and weight restrictions by the end of 7th February, pending full repair.
    - Provincial Highway No. 20 where an adjacent water pipeline burst and the road was temporarily closed for repairs. Eventually re-opened around 14th February.
    - Provincial Highway No. 86, Bridge No. 24, approximately 29 km west of the epicentre, where the shaking damaged specific bridge beam support pads (approximately 500 mm eastward displacement) for the eastbound lanes.
- High speed rail was temporarily suspended for line inspections but full service reinstated by late 7th February. Local railway operated by the Taiwan Rail Corporation continued service, albeit at reduce speeds in some areas with modest line damage. Services were fully restored by 18th February.
- Cracks on the embankment crest at the 15.3 m high Hu-Tou Pi Dam were observed but did not require any emergency action and the cracks were immediately repaired. Horizontal free field PGAs recorded at this location included 0.19g longitudinally and 0.29g in the transverse direction [20]. No other dams were adversely impacted.
- Residential reticulated water supply was interrupted to 400,000 households in Tainan City and 300 households in Chia-Yi City (north of Tainan City). By 8th February supply had been restored to all but 50,000 households, which reduced to 5,000 households by 13th February. All supplies that could be restored were completed by 21st February. The collapse and subsequent demolition of the Weiguan Building impacted on a major water supply pipeline, which was located beneath the edge of the road opposite the building site. A temporary above ground pipeline was initially installed to restore supply as quickly as possible.
- Power outage to approximately 173,000 households. Power was restored to all but 420 households by 7th February. Those households where power was not restored were all within collapsed buildings that have now been demolished.
- Interruption of reticulated residential gas supply to approximately 1,300 households with supply reinstated to most by 8th February. Supply to 207 households was not completed due to building collapse or customers switching

to bottled gas. Propane tanks are the predominant fuel locally, which is why there were relatively few reticulation outages. Also, plastic pipes are used for gas distribution, which performed well and contributed to the limited damage.

- Landline telephone service to 1,248 households was interrupted but restored by late 7th February. Service associated with 143 cell phone transmission facilities was also temporarily affected but restored by 8th February. Six mobile base stations and 13 free local calling centres were established at disaster response sites in Tainan City.
- Temporary shutdown of Unit 2, Hsinta Coal-fired Power Plant, Cieding District, Kaohsiung City.
- Maanshan NPP's two nuclear generating units were unaffected and remained operational.
- Temporary shutdown of one electrical distribution substation in mountain area of Tainan and at the Longtien Secondary Substation.

BUILDING COLLAPSE INVESTIGATIONS

The investigation into the collapse of the Weiguan building was concluded in early April 2016 (Tainan Court website, 7 April 2016 news). Five people, including the developer, design manager, two architects and a structural engineer were charged. The investigation found the main reasons contributing to the building collapse were inadequate design, poor construction, and lack of design review and construction monitoring, all of which resulted from the developer's intent to reduce the design and construction costs and therefore not meeting legal requirements. The combination of these acts resulted in a significant reduction of the building strength.

INFLUENCE OF IMPROVED DESIGN STANDARDS POST 1999

As described in the background section, there has been significant revision to seismic design standards in Taiwan in the last 50 years, as well as an increased awareness due to significant earthquakes such as Chi-Chi in 1999. As noted, significant increases in the seismic design loads were implemented in 1997.

Although it is difficult to draw conclusions on the effect of changes in design standards without conducting a more extensive survey of building damage, there were noticeable trends in the observed damage. Almost all of the collapsed and severely damaged buildings observed were constructed within a 10-year window between 1988 and 1998. No significant damage was reported to buildings designed and constructed post-1999 and most of the older mixed-use privately owned buildings performed adequately. Of the collapsed and severely damaged buildings, the majority appeared to be due to column failures on the ground floor due to a combination of poor structural configuration and detailing. There are several factors that may have contributed to the improved performance of more recent buildings, including the increase in seismic design loads implemented in 1997, the improved structural configuration and soft-storey design provisions, and improved awareness of good reinforcement detailing practice post Chi-Chi earthquake.

Seismic Design Actions

It is expected that the increased seismic design loads implemented in 1997 have increased the resilience of modern structures in Taiwan. However, many residential buildings constructed prior to the 1980s performed adequately, including the 2-6 storey mixed-use buildings that line most urban streets. Despite the low seismic design loads in standards at the time, these non-engineered buildings appear to have been constructed with sufficient strength to withstand moderate to large earthquakes. This strength is predominantly due to the practice of using infill walls. However, as taller buildings started to be built in the 1980s and 1990s, the same style of construction was used. The demands during the Meinong earthquake exceeded the capacity of many of these 5-16 storey buildings with the columns acting as critical structural weaknesses. Irrespective of strength, the seismic response of these buildings is considered to be non-ductile and more widespread damage and building collapse would be expected during larger earthquakes.

Building Configuration and Structural Systems

When not properly considered, the use of infill walls and open ground floor space can lead to a torsional and potentially soft-storey configuration. Changes to design provisions to check for soft-storey based on stiffness have been implemented, but may be ineffective unless the infill walls are considered in the analysis. More recently constructed buildings in Tainan appeared to have more regular reinforced concrete frames with the addition of reinforced concrete walls. The increased use of walls is likely to have offset the stiffness discontinuities in the open ground floor areas. Research into reinforced concrete walls is a strong focus at the National Centre for Research on Earthquake Engineering (NCREE), as is the use of innovative low damage systems such as rocking concrete and steel components and buckling restrained braces, which are commonly used in high-rise buildings in Taipei and Kaohsiung.

Seismic Detailing Practice

As reported, poor detailing practices were observed in many of the columns in the collapsed and severely damaged buildings. Splices in all of the longitudinal reinforcement at a single location contributed to the concentration of damage in the columns in Figure 24 and Figure 28, and were also noted in the Weiguan building. Concrete design standards in Taiwan now require lap splices to be staggered, similar to New Zealand requirements in NZS 3101:2006.

As was observed during the Chi-Chi earthquake, inadequate anchorage of stirrups and ties led to non-ductile column behaviour. The use of 90-degree hooks to anchor stirrups at corners and for cross ties has been proven during many earthquakes to be ineffective once the cover concrete spalls. Despite being required by concrete design standards in Taiwan for some time, 135-degree hooks were not commonly specified or used during construction of older buildings. An increased awareness following the Chi-Chi earthquake has improved the detailing of reinforcement anchorages, but this is dependent on adequate construction monitoring to ensure that correct practice is followed.

Quenched and Tempered Steel

The use of quenched and tempered high strength reinforcing steel was widespread in Taiwan during the 1990s. As noted in New Zealand more recently the use of quenched and tempered steel can be problematic, particularly when bending and using threaded couplers. Bends in quenched and tempered reinforcement are prone to cracking and can subsequently fracture when loads are applied. The fracture of stirrups in the columns shown in Figure 25 and Figure 30 may have been the result of quenched and tempered steel. The use of this steel declined following the Chi-Chi earthquake and the findings of research preformed at NCREE in 2000. It was banned with the introduction of a new reinforcement standard in 2013 (CNS 560).

Design Review and Construction Monitoring

Changes in design standards can only go so far and must be followed up with design review, approval of designs, and construction monitoring. The 50 m height limit that triggers a design peer review has been in place since the 1980s. This limit was identified as an issue following the Chi-Chi earthquake, but no change in policy was implemented. Most of the collapsed buildings in Tainan fell within this limit, including the Weiguan building that was reported to be approximately 49 m high. This height rule and the required design review and approvals needs to be reconsidered.

Adequate construction monitoring and approval processes are considered critical to ensure that buildings are constructed in accordance with the intended design. The core wall building shown in Figure 28 is a good example of this, with the drawings indicating 135-degree hooks on all stirrups and ties, but the damaged column revealing that 90-degree hooks were used, as was common practice by contractors at the time.

A review of aspects of building legislation is currently being conducted in Taiwan, including enhancing the requirements for construction monitoring.

SEISMIC ASSESSMENT AND RETROFIT OF EXISTING BUILDINGS

As illustrated in the background and building damage sections, a large number of older buildings have been designed to a lower seismic hazard than required by current design standards. On top of this, the configuration and detailing of older buildings can lead to potential non-ductile behaviour and collapse during earthquakes. As with many other countries, the process of assessing and strengthening these earthquake prone buildings has been recognised as a major issue for Taiwan in order to improve the seismic resilience of their building stock.

Successful seismic assessment and/or retrofit programmes had been initiated for public buildings, including district office buildings and schools, as described below in more detail.

Residential Buildings

Despite the vulnerability of typical Taiwanese buildings being well documented in past earthquakes, the uptake of seismic retrofits has been low. There is currently no legislation that requires seismic assessment or retrofit of privately owned buildings. Agencies such as NCREE and the Architecture and Building Research Institute of the Ministry of the Interior have initiated research into this area with the aim of developing simple retrofit solutions for critical structural weaknesses. Further information can be found on the following website: http://streethouse.ncree.narl.org.tw/

In April 2016, the Taiwanese Government launched a major 6-year, NT$50b ‘Home Stabilising Programme’ in response to the Meinong earthquake [25]. The programme is fully funded by the central government and implemented by local authorities. The programme covers three main aspects:

- Subsidising initial and detailed seismic assessments of old private residential buildings (NT$16b): full subsidy for the initial assessment (NT$6,000 for buildings less than 3,000 m^2 and NT$8,000 for buildings more than 3,000 m^2), and 45% subsidy for the detailed assessment (up to NT$300,000 each) should the initial assessment raise concerns. Private owners of residential buildings that received consents prior to 31 December 1999 can make the application through their local authorities.
- Subsidising the strengthening or rebuild of old private residential buildings (NT$22b).
- Subsidising local authorities to develop detailed maps of liquefaction potential and to pilot land improvement projects (NT$12b).

It is estimated that in total 769,000 initial assessments and 33,000 detailed assessments would be required. For the first two years, assessments will be prioritised for apartments, high-rise residential buildings, and buildings with soft-storeys. For the rest of the residential buildings, local authorities are expected to prioritise assessments based on the building age, location and geology, and review budgets every year. It was expected that 83,000 initial assessments and 2,000 detailed assessments would be undertaken in 2016.

The programme does not set any mandatory requirement for seismic assessments and strengthening, instead relying on financial incentives. It will be interesting to track the uptake and effectiveness of this approach when compared to the earthquake prone building policies in New Zealand.

School Buildings

The Chi-Chi earthquake in 1999 caused extensive damage to a number of school buildings. School buildings in Taiwan are constructed of reinforced concrete beam column frames with infill walls between the classrooms and are typically two to four storeys in height. The classroom buildings typically have reasonable strength transversely but are deficient in strength longitudinally. The Chi-Chi earthquake became a significant milestone for the government to review its building portfolio. The Ministry of Education along with NCREE have undertaken a comprehensive and systematic approach to the review, assessment, prioritisation and seismic strengthening of school buildings in Taiwan (http://school.ncree.org.tw, [9, 26-28]). A four stage approach has been undertaken, and includes an initial survey, a preliminary evaluation, detailed evaluation, and retrofit design and construction. The simple screening approach compares total floor area with resisting element area, such as walls or columns, on the ground floor. The preliminary evaluation takes the information gathered from a half day site survey and makes initial estimates of demand and capacity. The detailed evaluation is similar to the New Zealand Detailed Seismic Assessment procedures. The assessment approach has been verified and refined by full scale testing of existing classroom buildings [29].

An initial survey of 12,549 buildings was completed in August 2005. From the initial survey, budgets and more detailed assessments followed. Subsequently, a large number of school buildings have been identified as being of insufficient seismic strength and have been seismically strengthened. A suite of standard strengthening solutions has been provided to schools and structural engineers for this enhancement. These alternatives include the introduction of concrete shear walls, supplementary moment frames, jacketing of columns, or installation of supplementary steel bracing, as illustrated by the examples in Figure 42. As of March 2016 there have been 801 buildings strengthened and 353 buildings are undergoing redesign or in construction.

a) New concrete shear wall

b) New wing walls to the existing columns

c) New concrete shear walls

Figure 42: Example of school building strengthen methods (Source: NCREE).

In general, the school buildings which had seismic strengthening completed performed well during the Meinong earthquake. There was one school which had most of its buildings strengthened. The strengthened buildings typically sustained little or no damage, but the buildings still awaiting construction suffered a moderate level of damage. Some of the damage was in URM wall infills.

Of note was that all the schools that had undergone seismic strengthening had a plaque in a prominent exterior position which labelled exactly what had been strengthened in the building, as shown in Figure 43. In addition to providing a clear record to the building users of the work performed it is also of great assistance in any initial post seismic response review.

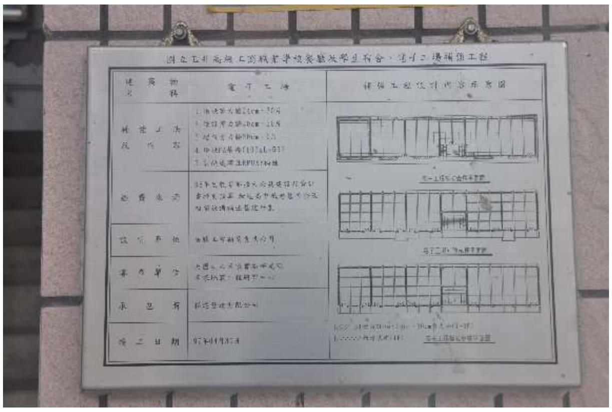


Figure 43: Classroom building strengthening plaque.

District Office Buildings

The district office (or local council) buildings provided an interesting case study of the implementation of seismic strengthening of earthquake prone buildings. The district office buildings were constructed using a standardised configuration consisting of 2-3 different variations with some customisation and/or additions over time. As well as providing comparisons of the seismic behaviour of geographically spread identical buildings, the district offices have a poor structural configuration and non-ductile detailing. Due to the vulnerabilities of these buildings and poor performance during previous earthquakes, a mandated strengthening programme had been initiated that required seismic strengthening of all public buildings constructed prior to 1997, as described in the background section. This programme provided an opportunity to compare the observed performance of original and retrofitted district office buildings.

The district offices are typically 2-3 storey reinforced concrete buildings constructed in the 1970-1980s. A typical floor plan is shown in Figure 44, with some offices extending with additions at the rear of the building. In the short direction of the building, lateral load resistance is provided by reinforced concrete frames with brick masonry infill. In the long direction of the building, lateral load resistance is provided by reinforced concrete frames, with two small masonry infilled walls near the stairs. The ground level is a large open plan office, whereas the upper levels contained offices with heavy masonry partition walls. This structural configuration resulted in both torsional eccentricities in plan and stiffness irregularity in elevation.

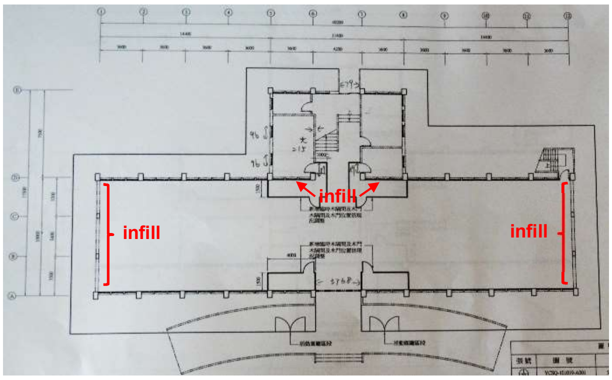


Figure 44: Typical floor plan of a district office building.

The observed damage to three district office buildings that had not been strengthened is shown in Figure 45. These offices were in Zuozhen, Nanhua, and Shanshang districts, where significant PGAs were recorded. In all three of these buildings, damage occurred to the ground level columns at the front of the building with wide inclined cracks, spalling and crushing of concrete. The infill walls stiffen the frame at the back of the building, and so the front frame is expected to experience larger deformations due to torsion. On top of this, the half-height infill below the window openings results in a short column effect (or captive column as referred to in Taiwan). The column restraint resulted in increased shear demands and with non-ductile detailing these columns were susceptible to shear failure. As with other buildings described earlier, the location of rainwater downpipes within the column core further reduced the capacity of the already slender columns. The columns in the Nanhua building were the most severely damaged, and did not appear to have much residual axial capacity, with the building appearing to be not far from collapse. Interestingly, the columns in the Nanhua building were smaller than the other buildings, being 360×500 mm compared to 400×600 mm. Damage to the infill walls in the Nanhua and Zuozhen buildings was relatively minor, with the building having sufficient lateral load resistance in the short direction. More significant infill wall damage was observed in the Shanshang building, with large diagonal cracking in the infill walls near the stairs, while the infill walls at the ends of the building preformed adequately. The Shanshang and Nanhua offices were still in use one month after the earthquake and were in the process of being vacated. It is not known if these will be demolished or repaired. The Zuozhen office on the other hand had continued to be used since the earthquake.

a) Zuozhen district

b) Nanhua district

c) Shanshang district (Source: Purdue University)

Figure 45: Examples of original district office buildings.

Recognising the risk from these buildings, a government order was enacted following the Chi-Chi earthquake that required all public buildings constructed before 1997 to be assessed and, if necessary, strengthened. Almost all of the district offices would fail a seismic assessment due to the vulnerabilities described above. The Tainan City region has a total of 37 district offices. At the time of the Meinong earthquake, 20 of these had been strengthened (54%). Three examples of these strengthened district offices are shown in Figure 46.

The Guiren district office (Figure 46a) was 3 storeys and of typical floor plan. The building was retrofitted in 2011 with the addition of 4 reinforced concrete walls. These walls were installed full height at the front and rear of the building to increase strength and maintain symmetry for lateral resistance in the long direction of the building. The walls were 250 mm thick with a double layer of reinforcement in each direction, and were installed within the existing reinforced concrete frames, with reinforcement embedded into the existing beams and columns. The added walls at the front of the building have been made a feature with green tiles. With the loss of only a few windows, this retrofit was considered an economical and attractive solution. Despite being located in close proximity to a number of severely damaged and collapsed buildings, the Guiren district office performed well during the Meinong earthquake with only minor damage observed. The walls successfully prevented the column damage that occurred in the un-strengthened district office buildings, and only minor cracking was observed at the interface between the retrofitted concrete walls and the adjoining columns.

The 3-storey district office in Guanmiao (Figure 46b) was particularly grand looking with large wrap around balconies. The building had been retrofitted in 2013 with the installation of 10 reinforced concrete walls. The masonry infill in the walls at the ends of the building had been replaced with reinforced concrete walls in each of the 3 frame bays. In the long direction of the building, a total of 4 reinforced concrete walls were added, located in the last bay of the frames in the corners of the building. As with Guiren, the walls had been made an attractive feature of the building and a gold plaque on the side of the building clearly outlined the retrofit measured. Although only inspected from the outside, the Guanmiao building appeared almost undamaged, with the retrofitted reinforced concrete walls preforming well. Guanmiao was close to the earthquake epicentre and experienced some of the largest intensity ground motions. The excellent performance of the building compared to the damage observed in un-strengthened district office buildings is a good example of successful seismic intervention.

The Yujing district office (Figure 46c) was slightly unusual, with only two storeys and an unconventional floor plan. The building had been retrofitted with a combination of reinforced concrete walls and steel braces. The steel braces are visible in the end bays at the front of the building, and in the upper levels on the side and rear, with concrete walls below. Yujing is located between Shanshang, Zuozhen, and Nanhua where the district offices were all severely damaged during the earthquake (Figure 45). The Yujing building suffered only minor damage during the earthquake, with cracking in the infill partition walls. However, the structural system performed well and as with the other retrofits damage to the non-ductile columns was prevented.

The earthquake observations highlighted the success of three different strengthening techniques and configurations. Based on the performance of the original and strengthened district offices, it is clear that the programme has increased the seismic resilience of these communities and allowed critical post-disaster facilities to remain operational.

a) Guiren district

b) Guanmiao district

c) Yujing district (Source: Purdue University)

Figure 46: Examples of retrofitted district office buildings.

Repaired Earthquake Damaged Building

A number of buildings in Tainan had been damaged and repaired following previous earthquakes, particularly the 2010 Kaohsiung Jiasian earthquake. Pre-existing damage is obviously difficult to ascertain when conducting visual inspections, but anecdotal evidence provided some insights. One particular example was a group of apartment buildings in Guiren, where two of the buildings were a mirror image and positioned side-by-side. As shown in Figure 47, the two buildings are five storeys high and were constructed in 1992. The damage to Building A was described previously and shown in Figure 24 and Figure 25. The columns experienced severe axial-shear failures and were shown to have a number of poor detailing practices (Figure 47b). The columns in Building B were apparently damaged during the 2010 Kaohsiung Jiasian earthquake, with column damage similar to that observed for Building A during the Meinong earthquake. The columns in Building B were subsequently repaired and retrofitted using a concrete jacketing technique with additional reinforcement and concrete installed to encase the damaged columns. The retrofitted columns in Building B are shown in Figure 47b, and are noticeably larger than the respective Building A columns. The retrofit appeared to have worked, with minimal column damage observed following the Meinong earthquake. Instead the increased stiffness of the retrofitted column had shifted the earthquake deformations and damage into other parts of the building, notably the arched concrete beams that frame into the column. Interestingly the columns in Building A had not been damaged during the 2010 Kaohsiung Jiasian earthquake and so had not been strengthened at the time. This decision appeared to lack foresight, with the building not surprisingly following a similar fate during the latest earthquake.

a) Two identical buildings

b) Original column (A) *c) Retrofitted column (B)*

Figure 47: Repaired and retrofitted building.

Another point of interest was a third building (C) in the block that was identical to buildings A and B, but orientated at 90 degrees. Buildings A and B were positioned in an E-W direction along one road, while Building C was positioned N-S along another road. Building C suffered only minor damage during the Meinong earthquake, indicating potential larger ground accelerations in the E-W direction which was also highlighted in the spectra shown in Figure 6.

Future Considerations

Initial discussions with government officials reflected on the difficulties of implementing a comprehensive assessment programme across the wider building portfolio. The ability to effectively influence and implement a scheme taking account of public reaction and willingness would be considered a major challenge.

SOCIAL AND ECONOMIC IMPACTS AND INITIATIVES

Awareness of Risk and Preparedness

In general, Taiwanese are well aware of the risks and potential impacts of earthquakes. As described in the background section, significant and regular past earthquakes have contributed to this general awareness. However, the risks associated with structural and geotechnical hazard have not necessarily been well conveyed or understood. People may consider the benefits and reduced risk of a new building when purchasing a house, but the uptake of retrofits in older privately owned buildings is low. There is a general perception that if a building survived previous large earthquakes (e.g. Chi-Chi in 1999) it will be okay in future earthquakes.

On 14 March 2016, the Taiwanese government released an online database of some areas in Taiwan that are prone to soil liquefaction. This data mainly came from previous geological surveys undertaken for major public construction projects and as such they are categorised as ‘Level 1’ (initial) investigations. ‘Level 2’ (medium level) investigations are to be undertaken by local authorities and the results will be publicly released through downloadable online databases. Subsidies are to be provided by the central government as set out in the ‘Home Stabilising Programme’. ‘Level 3’ (high level) investigations are to be undertaken for individual projects by developers.

Similar to the residential land categorisation released in New Zealand by the Ministry for Business, Innovation and Employment after the Canterbury earthquakes, residents are able to locate an address and check if their homes are in liquefaction-prone areas that are likely to suffer serious land damage in a major earthquake. It has been reported that public concern arose after the Meinong earthquake due to the potential link between soil liquefaction and the collapse of the Weiguan building, which may have contributed to the decision to release the liquefaction database. The release of the soil liquefaction information was expected to impact the real estate market with some predicting a drop in home value by 15% for the worst affected areas. Although preliminary in nature and accompanied by some guidance on the interpretation and use of the database, the local media report that the release of this information has had a significant public reaction, which is also similar to the Christchurch experience. The Taiwanese government has allocated significant resource to improving the understanding of liquefaction-related hazard and its mitigation over the next several years, along with identifying vulnerable buildings.

Similar to the residential land categorisation released in New Zealand by the Ministry for Business, Innovation and Employment after the Canterbury earthquakes, residents are able to locate an address and check if their homes are in

liquefaction-prone areas that are likely to suffer serious land damage in a major earthquake. It has been reported that public concern arose after the Meinong earthquake due to the potential link between soil liquefaction and the collapse of the Weiguan building, which may have contributed to the decision to release the liquefaction database. The release of the soil liquefaction information was expected to impact the real estate market with some predicting a drop in home value by 15% for the worst affected areas.[3] Although preliminary in nature and accompanied by some guidance on the interpretation and use of the database, the local media report that the release of this information has had a significant public reaction, which is also similar to the Christchurch experience. The Taiwanese government has allocated significant resource to improving the understanding of liquefaction-related hazard and its mitigation over the next several years, along with identifying vulnerable buildings.

Amendments to the Disaster Prevention and Protection Act were passed on 13 April 2016 [30]. For the first time, soil liquefaction is listed as a disaster cause under the Act. The amendments also included ten new clauses to enhance the relief measures during the disaster recovery phase.

Legacy and Museums

Following the Chi-Chi earthquake, the 921 Earthquake Museum of Taiwan was established in 2001 (http://www.921emt.edu.tw). The museum aims to educate the public on earthquake hazard and risk mitigation and act as a memorial to the devastation caused by past earthquakes. The museum is located on the old site of the Kwangfu Junior High that was damaged during the Chi-Chi earthquake and includes preserved damaged school buildings and fault expression.

The nearby Chelungbu Fault Preservation Park was opened in May 2013 (http://cfpp.nmns.edu.tw). The park and the museum preserve the fault profiles enabling public education as well as promoting research of geology and earthquakes.

These two museums are excellent examples of post-earthquake initiatives that have successfully increased public awareness and preparedness for future earthquakes.

Early Warning System

Two different earthquake early warning systems have been developed and implemented in Taiwan. A regional early warning system was developed by the Central Weather Bureau (CWB) using the existing seismograph network [31, 32]. In additional, NCREE has developed an on-site early warning system [33, 34]. The on-site system is based on P-wave detection and can provide increased warning time and accuracy for earthquakes with a shorter source distance when compared to regional systems, making it well suited to Taiwan's geography and seismic hazard. The on-site early warning system can potentially provide between 10-45 seconds warning for source distances ranging from 50-300 km.

A combined on-site and regional early warning system has been implemented in a number of school across Taiwan with support from the Ministry of Education. The current project aims to install the full system in 25 schools (main stations) as well as sub-stations in a further 3,419 schools. The main stations include shallow buried sensors and a backup sensor mounted on the building, whereas the sub-stations have no sensors and act by receiving alerts from nearby main-stations. As of March 2016 the system has been installed in 21 main stations and 236 sub-stations. The early warning system in schools is used to activate alarms and signs that trigger students to either evacuate the building (ground floor), or to drop, cover and hold under desks (upper floors). Regular drills are conducted to prepare students to respond, as shown in Figure 48.

The early warning system was installed in a number of schools in Tainan and provided a warning of approximately 8.4s during the Meinong earthquake. Both the warning system prediction and the actual PGA recording were estimated as an intensity level 5 in the Tainan region.

The aim of the early warning system in schools is for life-safety and provides an additional control to mitigate the risk in older school buildings with structural deficiencies. However, the early warning system is also being adopted in the high-tech manufacturing sector to prevent large economic losses. A warning of just a few seconds is sufficient to trigger the shutdown and securing of plant and equipment that may be damaged during the earthquake.

Figure 48: School children responding during an earthquake early warning drill (http://www.narlabs.org.tw/en/science-impacts/eews.php)

Early Loss Estimation

The Taiwan Early Loss Estimation System (TELES) was established in 1998 [35]. TELES incorporates a large database of potential earthquake scenarios based on known faults. When an earthquake notification is issued by the CWB, the estimated source and characteristics of the recorded earthquake are used to query the database to extract matching earthquake scenarios. This process can be completed within 1-2min of the CWB notification and results in an impact alert being sent to emergency personnel and private clients. The TELES alerts are issued in three stages:

---

[3] http://focustaiwan.tw/news/asoc/201603140016.aspx

- Stage 1: Initial automated alert – typically within 2 min of CWB notification.
- Stage 2: Updated alert based on refined earthquake source information, fault rupture characteristics, etc. – approximately 6 hours after earthquake.
- Stage 3: Verified result – approximately 12 hours after earthquake.

During the Meinong Earthquake the TELES Stage 1 alert estimated 5-30 casualties, 1500 water line breaks, and NTD$180-550m losses, based on six possible scenarios on nearby faults. The initial estimate of building damage and losses was reasonably accurate when compared to the actual impact. However, the number of deaths was underestimated (117 compared with estimated deaths and serious injuries of 5-30). The underestimation of deaths was attributed to the fact that a significant portion of the deaths occurred in a single collapsed building (115 in the Weiguan building).

DATA COLLECTION AND SHARING

The NZSEE team was fortunate to be able to link up with a joint Taiwan-US reconnaissance and data collection exercise in Tainan. Teams from NCREE and Purdue University (supported by the US National Science Foundation and the American Concrete Institute) collected data on damaged and undamaged concrete buildings representative of both older and new construction. A total of 135 reinforced buildings, including 124 low-rise buildings (1-7 stories) and 11 high-rise structures (up to 23 stories) were surveyed. Data collected included GPS coordinates, hand sketches of floor plans, dimensions of structural and non-structural elements, earthquake damage, photographs, and structural and architectural drawings (if available). The full dataset is now publicly available at: https://datacenterhub.org/resources/14098

NCREE has also collected significant data on the performance of school buildings to support the school assessment and retrofit programme. Data collected following the Chi-Chi earthquake was critical to providing justification and guidance for the school retrofit program. NCREE anticipate that data collected following the Meinong earthquake can provide equivalent data for private residential buildings to help convince building owners to invest in appropriate strengthening measures.

In addition, the US Earthquake Engineering Research Institute (EERI) hosts a virtual clearing house that includes a number of reconnaissance reports and information from both Taiwanese and US institutions [36].

Remote Sensing

In addition to being employed by emergency management agencies, remote sensing techniques are increasingly being used on a more local scale by researchers and reconnaissance teams.

Within a few hours after the Meinong earthquake, Taiwan's National Cheng-Kung University used aerial photos of disaster sites to create 3D models, which were uploaded to Sketchfab on the same day that the earthquake struck. In addition, a private company that creates impressive Virtual Reality (VR) panoramas deployed within 4 hours of the earthquake and used aerial robots at 5 different locations to capture both 360° aerial panoramas and 4K video to document the earthquake damage.[4]

A number of reconnaissance teams used remote sensing tools such as LiDAR and drones equipped with high resolution cameras. A number of 3D models created from the images captured at damage sites were created by the GEER team which provide a unique perspective [20].

Access to Buildings

The friendliness and openness of Taiwanese people helped facilitate building inspections. Ad-hoc inspections of both public and private buildings were relatively easy with occupants more than happy to invite engineers and researchers in to observe and document damage. Owners and officials appeared to have nothing to hide, sharing building drawings and allowing photographs to be taken. In some cases, occupants went as far as to offer inspection teams food and water.

OBSERVATIONS AND LESSONS

Emergency Response and Recovery

Given the localised impact of the earthquake, the emergency management structure appears to have worked well with coordination at a local district level. The response to collapsed buildings allowed for the rescue of a large number of people by well-trained USAR teams. Additionally, the timely demolition of collapsed and severely damaged buildings enabled the city to recover quickly.

Despite appearing to be relatively unaffected one month following the earthquake, a number of tall residential buildings were still severely damaged and awaiting decisions on potential repairs. In several cases these buildings were still occupied despite having red or yellow placards. Consideration for relocation or temporary housing of residents in damaged buildings is critical for a city with such a large urban population and may be an issue during larger earthquakes when the damage is more widespread. A particular challenge in Taiwan is that the mixed-use function of most buildings often results in the home and business being located in a single structure, resulting in greater impact when the building is damaged and unable to be occupied.

The lack of cordons and barricading was a noticeable difference to Christchurch during the 2010/2011 Canterbury earthquakes and contributed to the perception of a fast recovery. The tolerable risk of occupants in damaged buildings appeared to be much higher than in New Zealand, and many buildings still posed a significant risk of collapse during aftershocks or future earthquakes. The approach to cordons and barricading during earthquakes with less aftershock activity than that observed during the Canterbury earthquake sequence should be considered in New Zealand.

Structural Performance

In general, structural damage was characteristic of non-ductile concrete buildings. Although already documented during many past earthquakes, the Meinong earthquake served as yet another reminder of the consequence of poor structural configurations and non-ductile detailing practices, including:

- Irregularities in plan and elevation resulting in torsional or soft-storey response.
- Shear failure of short (or captive) columns.
- Lap splices of longitudinal reinforcement in locations of potential inelastic behaviour.
- Lack of robustness of columns with widely spaced transverse reinforcement.
- Failure of poorly anchored transverse reinforcement, including 90-degree hooks in stirrups and ties opening up.

---

[4] https://irevolutions.org/2016/02/07/aerial-robotics-virtual-reality/

The widespread use of masonry and concrete infill in reinforced concrete frames leads to buildings being significantly stiffer and stronger than initially expected. Despite their era, typical 3-6 storey mixed-use buildings preformed adequately during the Meinong earthquake. Their inherent strength appears to be significantly greater than the lateral design loads at the time of construction and most were able to withstand shaking close to current design level earthquake levels. However, their configuration and detailing results in non-ductile behaviour and given an earthquake of sufficient intensity many of the buildings pose a significant collapse risk. Building owners and occupiers may not be aware of the risks associated with these buildings and are often of the view that if they have survived previous major earthquakes then they will survive future earthquakes as well. This raises a serious challenge of how to educate the public as to the risk of non-ductile buildings that appear to have survived the Meinong (and other) earthquakes with no visible damage.

The use of more structural concrete walls in new buildings will improve their seismic behaviour. Consideration of the infill partitions walls during the design process would allow for improved understanding of the expected dynamic properties of the building and avoid potential structural weakness due to irregularities.

The similarities of column failures in 5-16 storey apartment buildings warrants further investigation to determine if these critical structural weaknesses would be identified using current seismic assessment tools. The processes for identifying non-ductile column buildings in New Zealand should also be taken into consideration.

Given recent issues in New Zealand regarding the quality of imported reinforcing steel, the fracture of stirrups in many Taiwan buildings is a timely reminder of the importance of reinforcement ductility. The ductility of supplied reinforcement, and in particular quenched and tempered steel, should be given careful attention when monitoring the construction of buildings.

The Meinong earthquake again highlighted the importance of adequate construction monitoring and consenting regimes. Differences between structural drawings and as-built detailing were observed in some older buildings, e.g. stirrup spacing and anchorage details. There was insufficient evidence to determine if increased awareness following the Chi-Chi earthquake has improved this situation in Taiwan, but it should be noted that all of the collapsed and severely damaged buildings observed by the team were constructed prior to 1999.

Liquefaction Hazard

The process of liquefaction hazard identification in Taiwan appears to be based predominantly on machine drilled boreholes with associated SPT data, along with soil sampling and laboratory analysis for Atterberg Limits and particle size distribution. Down-hole shear wave measurements are also used. Experience in Christchurch tends to indicate that such methods are good for identifying liquefaction-vulnerable soils, particularly where the potentially liquefiable soil is relatively thick. However, liquefaction analysis based on high-quality Cone Penetrometer Test (CPT) data also provides efficient and effective identification of liquefaction-vulnerable soils as well as the ability to identify highly stratified (interbedded) soil deposits, which can have a significant impact on the degree of vulnerability of buildings (and other structures at the ground surface or buried) to liquefaction-related damage.

Assessment and Retrofit

The Meinong earthquake provided evidence of the success of post-Chi-Chi seismic mitigation programmes for schools and public office buildings. There were clear examples of the improved performance of strengthened buildings when compared to un-strengthened buildings of similar construction. By identifying critical structural weaknesses in the configuration and design of these buildings they have been able to implement effective retrofit measures, often utilising generic solutions for common building typologies. This approach could be adopted in New Zealand to address common structural weakness in older buildings, such as fall hazards in masonry buildings and non-ductile concrete columns.

The timing and resourcing of seismic strengthening programmes appears to be a challenge in both Taiwan and New Zealand. Following the Meinong earthquake the government has faced challenges with determining appropriate timeframes for both assessment and strengthening of privately owned buildings and has instead opted for a voluntary programme with financial incentives. There is potential for both countries to learn from the approaches and policies being implemented.

Labelling of strengthened buildings with metal plaques is an excellent idea and provides increased awareness of earthquake risk and the mitigation measures. The plaques on school and district office buildings provide technical information on what has been strengthened in the building. These plaques should be located in obvious positions and used to promote the building's improvements to occupants.

FUTURE LFE MISSIONS TO TAIWAN

Despite differences in construction typology, the underlying issues in Taiwan are similar to that faced in New Zealand. In addition, the strong connections between Taiwan and New Zealand mean that much can be learned from LFE missions. A few points to consider during future LFE missions to Taiwan include:

- The National Centre for Earthquake Engineering (NCREE) is a good contact point and is active in research, standards development, policy advice, and post-earthquake reconnaissance and data collection. They can provide technical briefings and assist with site activities.
- The National Science and Technology Centre for Disaster Reduction (NCDR) is a government agency that acts as a key advisor to the government in the areas of hazard mitigation, emergency preparedness, response and recovery. They can assist with liaising with central/ local government agencies and research institutes, providing briefings and arranging site visits.
- People in Taiwan are very open, collaborative, and friendly. Information is freely shared and access and support is generously offered.
- Access to buildings and drawings can be arranged by local hosts. Owners may hold building drawings on site and are more than happy to share when asked politely.
- Safety during building inspections should be given particular attention. Many hazards were not well labelled and barricading was seldom observed. The condition of buildings should be assessed from a safe distance and discussed with others with knowledge of the site prior to entering.
- The Emergency Management Information Cloud (EMIC), managed by the Central Emergency Operation Centre, provides real time information on disaster response and recovery. The Chinese version had frequent detailed updates on all aspects, but the English version was less detailed.

ACKNOWLEDGMENTS

The authors are extremely thankful to the Taiwanese agencies who kindly gave up their time to assist the NZSEE delegation. These include:

- National Center for Research on Earthquake Engineering (NCREE) and in particular director Prof. Shyh-Jiann Hwang and Dr. Chiun-Lin Wu.
- National Science and Technology Center for Disaster Reduction (NCDR) and in particular Secretary General Dr Wei-Sen Li.
- National Cheng-Kung University, including Prof. George Yao, Associate Prof. Yi-Hsuan Tu, and Associate Professor Wen-Jong Chang.
- Architecture and Building Research Institute, Ministry of the Interior.

Additionally, the team would like to thank the teams from Purdue University and NCREE, and in particular Prof. Santiago Pujol and Prof. Hwang for allowing members to join their reconnaissance efforts and sharing collected building data. The information provided by the Earthquake Engineering Research Initiate (EERI) via their virtual clearing house was also essential to the LFE preparations.

Lastly, the team would like to thank the New Zealand Society for Earthquake Engineering for the opportunity to visit the region affected by the 2016 Meinong earthquake in Taiwan, and thank the Ministry of Business, Innovation & Employment (MBIE) and the Earthquake Commission (EQC) for the financial support that they provided through the NZSEE Learning from Earthquakes programme.

REFERENCES

1 Brunsdon DR, Davey RA, Graham CJ, Sidwell GK, Villamor P, White RH and Zhao JX (2000). “The Chi-Chi Taiwan Earthquake of 21 September 1999”. *Bulletin of the New Zealand Society for Earthquake Engineering*, **78**(3): 196-217.

2 CIA (2016). "Taiwan". *The World Factbook*. Central Intelligence Agency (CIA). Web, 28 May 2016.

3 Yu SB, Chen HY and Kuo LC (1997). “Velocity field of GPS stations in the Taiwan area”. *Tectonophysics* 274: 41–59.

4 Clahan K (2016). “*Summary of the Geology and Seismology of the February 6, 2016, Mw 6.3 Meinong Earthquake, EERI Taiwan Earthquake Reconnaissance Briefing Webinar”*. Available from: http://www.eqclearinghouse.org/2016-02-taiwan/files/2016/05/EERI_Meinong-EQ_Geology_Seismology_kbc_rev1.pdf

5 USGS (2016). “*Poster of the Taiwan Earthquake of 05 February 2016 - Magnitude 6.4*”. U.S. Geological Survey. Available from: http://earthquake.usgs.gov/earthquakes/eqarchives/poster/2016/20160205.php

6 EERI (1999). “*Chi-Chi September 21, 1999, M7.7 Earthquake*”. Earthquake Engineering Research Institute. Available from: https://www.eeri.org/1999/09/chi-chi/

7 Buckle IG, Chang K-C and Hwang J-S (2000). “*Section 6: Performance of Highway Bridges in The Chi-Chi, Taiwan Earthquake of September 21, 1999: Reconnaissance Report*”. Ed.: Lee, G. C., Loh, C.-H. Technical Report MCEER-00-0003. Multidisciplinary Center for Earthquake Engineering Research, University at Buffalo, State University of New York.

8 Bruneau M and Tsai K-C (2000). “*Section 5: Building Damage in The Chi-Chi, Taiwan Earthquake of September 21, 1999: Reconnaissance Report*”. Ed.: Lee, G. C., Loh, C.-H. Technical Report MCEER-00-0003. Multidisciplinary Center for Earthquake Engineering Research, University at Buffalo, State University of New York.

9 NCREE (2009). “*Technology Handbook for Seismic Evaluation and Retrofit of School Buildings*”. Second Edition, NCREE-09-023. National Center for Research on Earthquake Engineering, Taipei, Taiwan. (in Chinese).

10 Chai J-F, Lin C-M, Kuo K-C, Lin F-R, Chang Y-W, Yang Y-S, Lin K-C and Lin C-C (2010). “*The ML 6.4 Taiwan Earthquake of March 04, 2010*”. Available from: https://www.eeri.org/2010/03/taiwan/

11 Chai J-F, Teng T-J and Tsai K-C (2009). “Development of seismic force requirements for buildings in Taiwan”. *Earthquake Engineering and Engineering Vibration*, **8**(3): 349-358.

12 CPA (2005). “*Seismic Design Code and Commentary for Buildings*”. Construction and Planning Agency (CPA), Ministry of Interior Affair, Taiwan. Available from: www.cpami.gov.tw

13 ACI (2002). “*Building Code Requirements for Structural Concrete and Commentary (ACI 318-02)*”. American Concrete Institute, Farmington Hills, MI, USA.

14 ACI (2005). “*Building Code Requirements for Structural Concrete and Commentary (ACI 318-05)*”. American Concrete Institute, Farmington Hills, MI, USA.

15 ACI (2016). “*Building Code Requirements for Structural Concrete and Commentary (Chinese, Traditional) (ACI 318C-14)*”. American Concrete Institute, Farmington Hills, MI, USA.

16 CPA (2015). “*Project on Seismic Evaluation and Remediation of Private Buildings*”. (In Chinese) Construction and Planning Agency, Ministry of Interior, Taiwan. Available from: www.cpami.gov.tw

17 Ministry of Justice (2016). “*Housing Act*”. Retrieved from: http://law.moj.gov.tw

18 CWB (2016). “*Meinong earthquake*”. Taiwan Central Weather Bureau. www.cwb.gov.tw

19 USGS (2016). “*M6.4 - 25km SE of Yujing, Taiwan*”. U.S. Geological Survey. Available from: http://earthquake.usgs.gov/earthquakes/eventpage/us20004y6h#general

20 GEER (2016). “*Meinong, Taiwan earthquake*”. Geotechnical Extreme Events Reconnaissance (GEER). Available from: http://www.geerassociation.org/index.php/component/geer_reports/?view=geerreports&id=73

21 NCREE (2016). “*The February 6, 2016 ML-6.6 Meinong, Taiwan Earthquake and Lessons Learned*”. Report prepared by the National Center for Research on Earthquake Engineering (NCREE) Taiwan. Available from: http://www.eqclearinghouse.org/2016-02-taiwan/reconnaissance-reports/

22 Tu Y-H (2016). “*2016/02/06 Meinong Earthquake, Kaohsiung, Taiwan: Reconnaissance Report ver. 2.0*”. Available from: http://www.eqclearinghouse.org/2016-02-taiwan/reconnaissance-reports/

23 NCREE & NCKU (2016). “*0206 Meinong Earthquake – Report on Emergency Evaluation of School Buildings*”. National Center for Research on Earthquake Engineering (NCREE) and National Cheng-Kung University (NCKU). Taiwan. (in Chinese)

24 NCDR & NCREE (2016). “*0206 Earthquake Damage Record and Field Investigation Report*”. National Science

and Technology Center for Disaster Reduction (NCDR) and National Center for Research on Earthquake Engineering (NCREE), Taipei, Taiwan. (in Chinese).

25 CPA (2015). "*Home Stabilising Programme*". Construction and Planning Agency, Ministry of the Interior, Taiwan. Available from: www.cpami.gov.tw

26 Hsiao F-P, Oktavianus Y, Ou Y-C, Luu C-H and Hwang S-J (2015). "A pushover seismic analysis and retrofitting method applied to low-rise RC school buildings". *Advances in Structural Engineering*, **18**(3): 311-324.

27 Hwang SJ, Chung LL, Jean WY, Yeh YK, Sher CW, Chang HC, Wang YK and Chen YT (2006). "*Implementation Planning for Seismic Evaluation and Retrofit of Elementary School Buildings (II)*". NCREE-06-004, National Center for Research on Earthquake Engineering, Taipei, (in Chinese).

28 Tu Y, Yeh P, Liu T and Jean W (2009). "Seismic Damage Evaluation for Low-Rise RC School Buildings in Taiwan". *Structures Congress*, 1-10.

29 Jaung W-C, Chiou T-C, Tu Y-H and Hwang S-J (2008). "In situ pushover test of school building structure of Sin-Chen junior high school in Hualien county". *Journal of the Chinese Institute of Civil and Hydraulic Engineering*, **20**(4): 495-507.

30 Ministry of Justice (2016). "*Disaster Prevention and Protection Act*". Retrieved from: http://law.moj.gov.tw

31 Hsiao N-C, Wu Y-M, Shin T-C, Zhao L and Teng T-L (2009). "Development of earthquake early warning system in Taiwan". *Geophysical Research Letters*, **36**(5): L00B02.

32 Hsiao N-C, Wu Y-M, Zhao L, Chen D-Y, Huang W-T, Kuo K-H, Shin T-C and Leu P-L (2011). "A new prototype system for earthquake early warning in Taiwan". *Soil Dynamics and Earthquake Engineering*, **31**(2): 201-208.

33 Lin C-C, Lin P-Y, Chang T-M, Lin T-K, Weng Y-T, Chang K-C and Tsai K-C (2012). "Development of On-Site Earthquake Early Warning System for Taiwan, Earthquake". *Research and Analysis - New Frontiers in Seismology*, Dr Sebastiano D'Amico (Ed.), ISBN: 978-953-307-840-3.

34 Lin P-Y, Huang S-K, Chiang H-W and Shen Z-P (2012). "Development of the On-site Earthquake Early Warning System in System in Taiwan". *15th World Conference in Earthquake Engineering*, Lisbon, Portugal, 24-28 September.

35 Yeh C-H, Loh C-H and Tsai K-C (2006). "Overview of Taiwan Earthquake Loss Estimation System". *Natural Hazards*, **37**(1): 23-37.

36 EERI (2016). "*Taiwan March 4, 2010, M6.2 Earthquake*". Earthquake Engineering Research Institute. Available from: https://www.eeri.org/2016/02/taiwan/