NCREE REPORT

The February 6, 2016 M_L-6.6 Meinong, Taiwan Earthquake and Lessons Learned

Prepared for the Earthquake Engineering Research Institute's Learning from Earthquakes Program

National Center for Research on Earthquake Engineering (NCREE)
Taiwan

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I. Event Summary

On February 6, 2016, 03:57:26.1 (world time February 5 07:57:26.1), an earthquake of Richter magnitude scale of M_L 6.6 occurred in Meinong District of Kaohsiung City, Taiwan. The Earthquake Report No. 105006 released by the Seismological Center of the Central Weather Bureau, Ministry of Transportation and Communications (MOTC) (hereinafter referred to as the "CWB") showed that the epicenter was located 22.92^o North and 120.54^o East (27.1 km northeast from the Pingtung County Government) and had a depth of 14.6 km. This earthquake was felt all over the island of Taiwan. According to the earthquake report, the CWB real-time strong ground motion station CHN3 located in Sinhua District, Tainan City had the largest recorded peak ground acceleration of 401 cm/s^2 in the east–west direction. The ground shaking level at CHN3, having an epicentral distance of 25 km, just slightly crossed the threshold of CWB-defined Intensity Level 7 (i.e., PGA greater than 400 cm/s^2). The shaking detected at Caoling, Yunlin County, reached CWB-defined Intensity Level 6. Regions that experienced Intensity Level 5 include: Pingtung, Kaohsiung, Tainan, and Chiayi. Intensity Level 4 shocks were felt at: Taitung, Nantou, Changhua, and Taichung. All other regions, with the exception of Taipei, experienced at least Intensity Level 1 shocks. Real-time Seismic Network of the National Center for Research on Earthquake Engineering (NCREE), National Applied Research Laboratories (NARLabs) also detected shock waves of peak ground acceleration of 408 cm/s^2 at Puzai Station (station code: A730) in Nanhua District, Tainan City, which was located 21.5 km away from the epicenter. The recorded acceleration histories are available for download at URL http://www.ncree.org/Ncree.aspx?id=17

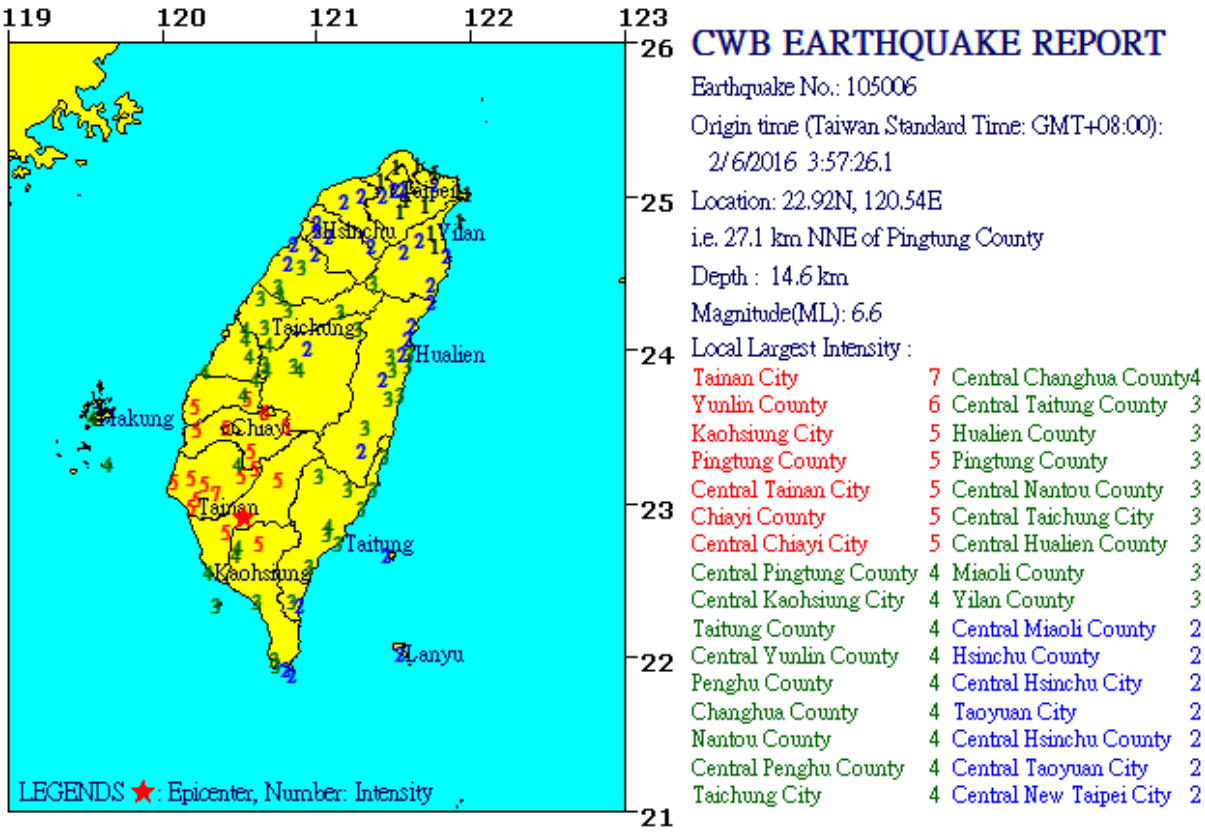


Figure 1.1 Earthquake Report released by the CWB

II. On-site assessment for seismic damage - Buildings

Building damages caused by this earthquake mainly occurred in the Tainan region. Once the earthquake occurred, personnel of the NCREE immediately began to collect disaster information reported by online media in order to compile a preliminary list of disaster locations for building damages. These data were then provided to the disaster reconnaissance team to carry out damage assessments.

The building seismic damage reconnaissance team included: (1) Department of Architecture, and Department of Civil Engineering of National Cheng Kung University; (2) Department of Construction Engineering, National Kaohsiung First University of Science and Technology; (3) Department of Land Management and Development, and Department of Aviation and Maritime Transportation Management of Chang Jung Christian University; (4)

Architecture and Building Research Institute, Ministry of the Interior; (5) licensed structural engineers; and (6) NCREE and other supporting agencies and departments. Preliminary survey was conducted on February 6 for the primary aim of verifying disaster locations, damage mechanisms, and brief assessment of the extent of damages. The following sections shall report on the process and preliminary findings of the reconnaissance carried out at the disaster locations.

2.1 Weiguan Jinlong Building in Yongkang District

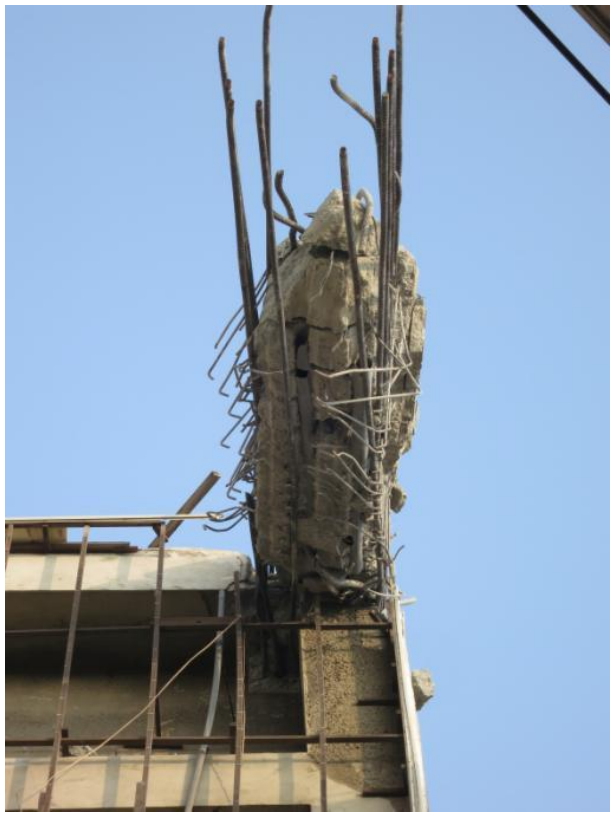
The Weiguan Jinlong Building was located at No. 139, Section 2, Yongda Road, Yongkang District, Tainan City and included 16 above-ground floors and 1 basement floor. The building was first built in 1994 primarily as a mixed-use residential and commercial building.

Figure 2.1 Aerial photographic view after the collapse of the Weiguan Jinlong Building in Yongkang District (provided by Ren-Zuo Wang)

The Weiguan Jinlong Building, unfortunately, collapsed during this earthquake (Figure 2.1), leading to 115 deaths and 96 injuries. Figure 2.2 survey

results showed that the main column reinforcement couplers were spliced in the same elevation. The reinforcements were detached from the coupler splices while the hook of column transverse reinforcements exhibited a non-seismic bending angle of only 90 degrees. The floor plan drawing currently available (Figure 2.3) showed that only a single bay was provided in the shorter structural axis, with very low structural redundancy. The building exterior facing Yongda Road had fewer walls. The rear side of the building, on the other hand, had more walls at the staircases and elevator lobbies. More damages were thus observed at the side of Yongda Road. The lower floors were allocated for commercial use and had less walls and probably less structural strength compared to the other floors. Most damages were tended to occur at these lower floors. During the earthquake, columns on one side of the building were mainly subjected to axial compressive forces, while columns on the other side were mainly subjected to axial tensile forces. The columns may be damaged if their strengths were unable to withstand the seismic forces. At the same time, rebar seismic detailing may be inadequate (transverse reinforcement may be too loose, the bends may have failed to be inserted into the concrete core, the main beam reinforcement may be improperly anchored to the column core, the coupler splices failed, or the main column reinforcements may be spliced in the same elevation) which resulted in lack of ductility and led to subsequent collapse during the earthquake. There were many factors that compromised the structure's ability to withstand earthquakes, leading to the collapse in the structurally weak layers of the building and horrendous casualties.

(a) Rebar coupler splices were located in the same elevation



(b) 90 degrees hook of the column transverse reinforcement

Figure 2.2 Photograph depicting the devastation of the Weiguan Jinlong Building in Yongkang District

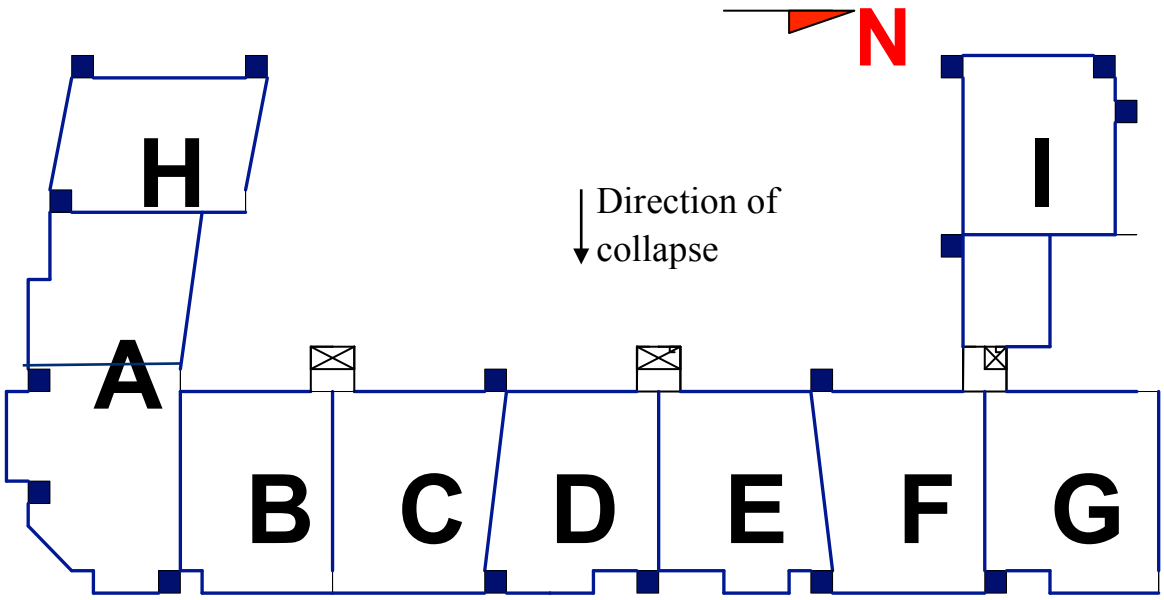


Figure 2.3 Floor plan layout of Weiguan Jinlong Building in Yongkang District (provided by Dr. Jui-Liang Lin)

2.2 King's Town Bank, Sinhua Branch

King's Town Bank is located at No. 586 Zhongshan Road, Sinhua District, Tainan. The building has 11 above ground floors and 1 basement floor. This building was constructed in about 1996 and was primarily a mixed-use commercial and residential building. The 2 bottom-most floors were allocated for the bank while floors 3 and above were undergoing renovations for a rental hotel. Hence, no one lived in the building at the time of the earthquake. When the earthquake occurred, no one was injured despite the building being tipped over. The bottom floors of the King's Town Bank building were allocated for commercial and had spacious interiors and higher ceilings. The bottom columns were thus subjected to extremely high axial stress, leading to axial damage of the columns near the driveway entrance and exits that resulted in the collapse of the building (as shown in Figure 2.4).

(a) Damages to the vertical elements at the bottom floors

(b) Axial damages to the column at the 1st floor

Figure 2.4 Collapse of the King's Town Bank Building in Sin-Hua District

2.3 Dazhi Village Market, Eastern District, Tainan City

Dazhi Village Market is located at Lane 103, Changdong Street, Eastern District, Tainan City. The Market has 4 above ground floors and 1 basement floor, and is a mixed-use commercial and residential building. This building is a series of connected apartment buildings. Due to the presence of the market, the first floor had only a brick wall at the corner and hardly any partitioning walls throughout the entire level, creating a structurally weak bottom layer. During the earthquake, the columns were subjected to axial damages that led to collapse of the weak layer (Figure 2.5). Only a small area with the brick wall did not collapse. Fortunately, the market was not yet open to the public during the earthquake. No one was trapped when the bottom layer collapsed. Only 1 person living in the residences on the upper floors was injured.

(a) Collapse of the building (b) Axial damage of the columns

Figure 2.5 Collapse of the Dazhi Village Market in the Eastern District

2.4 Xingfu Building, Gueiren District, Tainan City

This is a 7-story apartment building located at No. 46, Xinyi North Road, Gueiren District, Tainan City and was constructed in about 2000. The 1st and 2nd floors of this building were allocated for commercial use and thus had less walls at these layers. Building collapse occurred only in the 1st and 2nd floors while the upper structures basically remained intact. Additionally, as the structure was located at a corner of an intersection, asymmetry of the structural

system led to torsion which, together with structurally weak bottom layers, caused the building to collapse (Figure 2.6). 1 person was injured in this building.

(a) Collapse of the building

(b) Damaged connectors at the columns and beams

Figure 2.6 Collapse of Xingfu Building at Gueiren District (provided by Dr. Yu-lin Chung)

2.5 Lane 101, Taizi Road, Rende District, Tainan City

This apartment is located at Lane 101, Taizi Road, Rende District, Tainan City. The building has 3 above ground floors with an extra floor constructed using corrugated metal sheets atop the roof. The building was constructed in 1980. Since the building was constructed many years ago, the vertical elements failed to provide adequate anti-earthquake capabilities. Poor structural configuration also led to torsions in the structural system which led to the collapse of the structurally weak layer (Figure 2.7).

(a) Original appearance of the building (b) The collapsed building

Figure 2.7 The residential building at Lane 101, Taizi Road, Rende District, Tainan City

2.6 Residential building at Minzu Road, Yujing District, Tainan City

This building is located on Minzu Road, Yujing District, Tainan City, and is an ordinary house next to the street with 3 above ground floors. The building was constructed in 1989. Although this building did not collapse during the earthquake, there were obvious shearing damages of partitioning brick walls within the house (Figure 2.8).

(a) Shearing damages of the brick walls

(b) X-shaped shearing cracks on the brick walls

Figure 2.8 Residential building at Minzu Road, Yujing District, Tainan City

2.7 Jinxiu World Building

This building is located at Lane 141 of Dade Street, Southern District, Tainan City, and is a reinforced concrete building with 13 above ground floors. Post-earthquake survey found signs of shearing damages on non-structural walls of this building (Figure 2.9).

(a) Shearing damages of non-structural walls

(b) Shearing damages of staircase walls

Figure 2.9 Damages on RC walls of the staircase of Jinxiu World

2.8 Yujing Junior High School, Tainan City

Yujing Junior High School was located at No. 152, Dacheng Road, Yujing District, Tainan City at 120.4705^{o} east and 23.1238^{o} north. The school campus included 5 buildings - Subject Classrooms, Activity Center, Qinlao Building, Zhishan Building, and Pushi Building. The NCREE estimated that this campus was subjected to shocks that reached a CWB-defined shaking Intensity 5. The Subject Classrooms and Activity Center buildings in campus were damaged in this earthquake.

The Subject Classroom building is a reinforced concrete building with 3 above ground floors with corridors along one side of the building which are supported by column structures. The building was built in 1998. A number of building tiles came off the building during the March 4 Jiaxian Earthquake in 2010, while partitioning walls of the classrooms exhibited minor cracks. During this on-site survey, the school has already cordoned off the building and designated as a dangerous area. This earthquake generated shearing cracks along the columns of the 1st floor windows (Figure 2.10) with pronounced severity on the window columns at the backside. It was determined that constraints imposed by the windows at the top and bottom ends of the column led to severe diagonal shearing cracks, with the shears clearly exposing the steel reinforcements within the column (Figure 2.11). Additionally, the earthquake also caused ceiling panels along the edge of the building to fall off from the light steel frame at the 2nd and 3rd floors of this school building (Figure 2.12).

The Activity Center building is a reinforced concrete building with 3 above ground floors with corridors along one side of the building supported by column structures outside the corridors. The building was built in 1997. When entering the activity center, large quantities of debris from red bricks were found on the floor. After inspection, it was found that red bricks along the pipelines had broken apart and fell off during the earthquake (Figure 2.13). One can also see

visible cracks at locations near and above the stage along the bottom of the beams and the intersection with the red brick areas (Figure 2.14). Many diagonal cracks were also seen in the columns and nearby brick walls. Diagonal cracks could also be seen on the other side of the structure (Figure 2.15). After conducting internal damage assessments, the surveyors then observed damages to the building's exteriors. Tiles had fallen off the wall surfaces while windows had fallen onto the ground due to compression (Figure 2.16). Concrete blocks along the window frames were heavily damaged, and hung precariously while window glass panels were broken as well. The school was requested to seal these areas immediately on the same day to prevent people from being injured by falling objects (Figure 2.17). In addition to the building damages described above, many stainless steel water tanks toppled over as shown in Figure 2.18.

Figure 2.10 Diagonal cracks caused by shearing damages at the 1st floor window columns of the subject classrooms

Figure 2.11 Severe shearing damages at the backside of the window columns

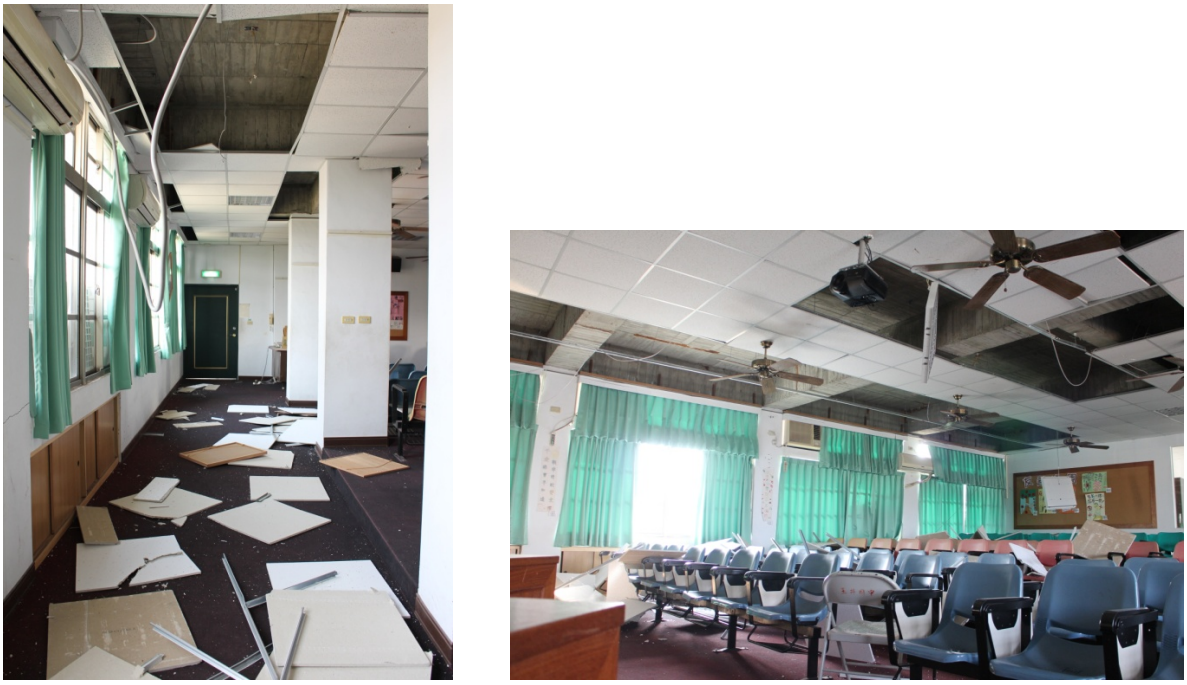


Figure 2.12 Subject Classroom building. Ceiling panels fallen from the light steel frame

Figure 2.13 Activity Center. Large quantities of red bricks along the pipelines that had fallen off during the earthquake

Figure 2.14 Activity Center. Cracks at the interface between the bottom of the beam and the brick wall at the bottom

Figure 2.15 Activity Center. Diagonal cracks along the walls which were also observed at the other side

Figure 2.16 Activity Center. Tiles had fallen off the wall surface. A number of windows panels had been subjected to compression and fell onto the ground

Figure 2.17 Activity Center. Concrete blocks forming the windows' outer frames hanging precariously as well as broken window panels.

Figure 2.18 Failure of many stainless steel water tanks at Yujing Junior High School

2.9 Tainan Municipal Beimen Elementary School (Yuhu Branch)

Beimen Elementary School (Yuhu Branch) is located at No. 39-3 Yugang

Village, Beimen District, Tainan City, with the coordinate of 120.1392° East and 23.2616° North. The school campus included a total of 3 buildings: West Block, South Block Classrooms, and North Block Classrooms. The NCREE estimated that this campus was subjected to CWB-defined Intensity 5 shockwaves. The campus building West Block was damaged by this earthquake.

The West Block is a reinforced brick building with 1 above ground floor constructed in 1984. It has corridors running along one side devoid of any column structures. During this on-site inspection, it was found that this school building had earlier jacketed 3 classroom columns with steel plates for reinforcement purposes at an unspecified date. A vertical crack was found at one location of an unreinforced classroom (Figure 2.19) not likely caused by seismic forces. It was determined that the internal steel reinforcements may have become corroded and swollen, and the earthquake simply enlarged the cracks in the concrete.

Figure 2.19 West Block. Vertical cracks along the columns. It was suspected that the internal steel reinforcements have become corroded and swollen. The earthquake simply enlarged the cracks.

2.10 Tainan Municipal Beimen Elementary School

Beimen Elementary School is located at No. 3, Jiucheng, Beimen Village, Beimen District, Tainan City, with the coordinates of 120.1251^{o} East and 23.2651^{o} North. The campus has a total of 6 buildings: West Block, Forward Block, Rear Block Classroom, Activity Center, Podium, and Kitchens. The NCREE estimated that this campus was subjected to CWB-defined Intensity 5 shockwaves. The campus building West Block was damaged by this earthquake.

The West Block is a reinforced brick building with 1 above ground floor constructed in 1970 has corridors running along one side devoid of any column structures. On-site survey found cracks at 2 locations of classroom columns of the school building (Figure 2.20). It was determined that the cause of the cracks was probably because the school was located near the coast with an unobstructed area facing the sea. Long-term exposure to sea sprays may have corroded steel reinforcements within the column and led to swelling. This earthquake then caused the column to break apart. The concrete was then broken apart to reveal that the inside had become hollow. Additionally, concrete spalling was observed on 1 column along the side of the corridors, exposing the reinforcements within the concrete (Figure 2.21). Initial assessments determined that this was probably caused by the corrosion and swelling of the steel reinforcements that led to cracks in the concrete. This earthquake then caused parts of this concrete to fall off.

Figure 2.20 West Block. Vertical cracks on the building's columns probably caused by corrosion and swelling of the steel reinforcements contained within. This earthquake than caused the cracks to appear.

Figure 2.21 West Block. Concrete peeling off from at the bottom of a column at the corridors. The exposed reinforcements were rusted which was probably not caused by this earthquake.

2.11 Gueiren Junior High School, Tainan City

Gueiren Junior High School is located at No. 2, Section 2, Wenhua Street, Houshi Village, Gueiren District, Tainan City with the coordinate of 120.294^{o}

East and 22.9704° North. The campus includes a total of 10 buildings, namely: Boxue Building, Lizhi Building, Chenggong Building, Xiangjiang Building, Yangming Building, Gezhi Building, Guanghua Building, Activity Center, Music Classroom, and Chinese Music Classroom. Seismic retrofit had been completed for 4 of these buildings, namely Yangming Building (addition of wing walls), Boxue Building (column enlargement), Lizhi Building (column enlargement and addition of wing walls), and Chinese Music Classroom (addition of wing walls). The retrofitted buildings were shown in Figure 2.22 to Figure 2.25, and experienced no structural damages during this earthquake.

Figure 2.22 Yangming Building. No structural damage.

Figure 2.23 Boxue Building. No structural damage.

Figure 2.24 Lizhi Building. No structural damage.

Figure 2.25 Chinese Music Classroom. No structural damage.

Two school buildings, namely Guanghua Building and Gezhi Building, were damaged in this earthquake. Guanghua Building is a reinforced concrete building with 3 above ground floors and corridors along one side of the building

that lacked column structures outside the corridors. The building was constructed in 1987. This school building underwent comprehensive building assessment in 2009. Outcomes indicated that the building lacked earthquake resisting capability (Capacity-to-Demand Ratio, CDR = 0.706) and must undergo retrofit procedure. Retrofit design was completed in the same year and the school is currently waiting for the budget for retrofitting the school building.

This on-site investigation found shearing cracks in multiple columns at the first floor of this school building, of which one the columns exhibited shear failure (Figure 2.26 and Figure 2.27).

Figure 2.26 Guanghua Building. Structural damage of the columns.

Figure 2.27 Guanghua Building. Structural damage of the columns.

Gezhi Building is a reinforced concrete building with 4 above ground floors with corridors along one side of the building that lacks column structures outside the corridors. The building was constructed in 1988. This school

building underwent comprehensive assessments in 2014. Outcomes indicated that the building lacked earthquake resisting capability (CDR = 0.969) and must undergo retrofit procedure. Retrofit design was completed in the same year and the school is currently waiting for the budget for retrofitting the school building.

This on-site investigation found that this building underwent shearing damages in its walls as well as damages to its expansion joints caused by collisions with neighboring buildings during the earthquake (as shown in Figure 2.28).

Figure 2.28 Gezhi Building. Damages to the expansion joints

2.12 Nanhua District Office

Nanhua District Office was located at No. 230 Nanhua Village, Nanhua

District, Tainan City, with coordinate of 120.4777^{o} East and 23.0430^{o} North. This building is a 3-story reinforced concrete building (Figure 2.29). The 1st floor is used for carrying out administrative tasks of the district office and lacked any partitioning walls. Only an infill brick wall was provided at the rear side of the building. Although the building did not collapse during this earthquake, there were significant shear failures observed on a large number of columns. The protective concrete cover spalled off from some of the columns, exposing the steel reinforcements as well as inlaid pipes contained within (Figure 2.30).

Figure 2.29 Nanhua District Office, a 3-story reinforced concrete building.

Figure 2.30 Windows have led to short column effects that led to shear failure to a large number of columns during the earthquake

2.13 Gueiren District Office (retrofitted; no structural damages)

Gueiren District Office is located at No. 2, Section 2, Zhongshan Road, Gueiren District, Tainan City with the coordinate of 120.2939^{o} East and 22.9672^{o} North. This is a 3-story reinforced concrete building (Figure 2.31). The first floor is an open space used for conducting day to day administrative affairs of the district office. This building was damaged during the Chi-Chi earthquake in 1999 and thus underwent seismic retrofit in 2011. A total of 4 shear walls were provided in the front and back sides of the building (Figure 2.32). No structural damage was observed after this earthquake, showing that the structural retrofit was capable of improving the overall earthquake resisting capability of the entire building.

Figure 2.31 Gueiren District Office, a 3-story reinforced concrete building

Figure 2.32 Shear walls built in the Gueiren District Office

2.14 Lessons learned and recommendations from the post-earthquake building damage surveys

(1) Outcomes of this survey found that seismic retrofit was effective in preventing damage. These included retrofit of school buildings of Gueiren Junior High School and Gueiren District Office. These observations demonstrated that the strategy of employing seismic retrofit for existing older buildings could greatly improve their earthquake resisting capabilities within a limited period of time and mitigate earthquake induced disaster.

(2) It would be recommended to accelerate seismic assessment and retrofit program of public markets, township offices, police departments, and fire stations.

(3) This survey also found that many mixed-use commercial and residential

buildings had poor structural system configurations, or were subjected to improper architectural layout changes that created structural failures due to structurally weak layers and/or excessive torsional eccentricity. The recommendation would prioritize privately owned buildings but provided for public usage (such as malls, shops, movie theaters, etc.) to obtain mandatory professional approval and certification for architectural layout changes (including partitioning) to ensure that the building's earthquake resisting capacity is sufficient in safeguarding public interests.

(4) Another recommendation is to accelerate the promulgation of provisions and laws for seismic assessment and retrofit of existing older buildings. All older buildings must undergo seismic assessments (and retrofit, if necessary) to get better prepared for the future earthquakes.

(5) An administrative documentation system to keep traceability of architectural and structural changes must be established for publicly used buildings to safeguard the lives and properties of the building users.

III. On-site assessment for seismic damage - Bridges and Roads

3.1 Bridge No. 24, Provincial Highway 86

On the day of the February 6 earthquake, media and construction section of the Directorate General of Highways (DGH) reported earthquake damages at the Dongshipu Bridge of Provincial Highway 3 located in Neimen District of Tainan City as well as Bridge No. 24 of Provincial Highway 86. Fortunately, these damages did not result in any injury of the commuters. In response, the NCREE mobilized personnel in the vicinity to implement survey checks of the damaged areas of the bridge. During the preliminary phase, a team composed of 3 individuals was dispatched to carry out various tasks. A team member was dispatched to the Dongshipu Bridge to conduct on-site inspection and found that the bridge pier sank by about 15 cm into the ground while cracks appeared on the approach shoulders. Damages were observed at the guard rail near the expansion joints at the sunken section of the bridge, while slight damages were seen in the P1 cap beams. The construction section immediately carried out emergency repairs of the road surfaces and opened one lane for the traffic to reduce the extent of traffic impact. The other 2 personnel were dispatched to Bridge No. 24 of Provincial Highway 86. Due to the earthquake, the bridge deck was displaced eastwards by about 50 cm according to measurements carried out by the construction section. Damages were observed for 5 bridge abutment supports as well as the top part concrete of 1 bridge abutment. Since damages to this bridge were more severe, the construction section closed the roads off to any traffic on the day to ensure commuter safety. For several days after the earthquake, the bridge disaster survey team mobilized 6 individuals using unmanned aerial vehicles (UAV) and portable LIDAR scans to conduct comprehensive surveys of the damaged bearings and bridge components of Bridge No. 24 of Provincial Highway 86. Records collected from the survey

would be used as a reference for subsequent research and to help draft recommendations for repairing the bridge and any necessary on-site testing plans as needed by the DGH.

3.2 Lessons learned and recommendations from the post-earthquake damage surveys for the bridges

The Meinong Earthquake did not cause major disastrous damages to the bridges which helped strengthen public confidence on the services and qualities of publicly constructed bridges. The disaster inspection records and work data collected also greatly supported research on improving strategies for responding to earthquake damages of bridges as well as anti-earthquake capacities of bridge designs. A total of 2 recommendations were proposed according to the outcomes of the disaster inspection of the bridges:

(1) The government and relevant units shall continue to improve and conduct reviews for bridge designs, construction plans, and construction monitoring and inspection processes.

(2) Seismic performance assessments and retrofit plans shall be constantly carried out for various bridges. Given that unseating prevention devices can effectively reduce bridge damages and any disastrous accidents that may occur afterwards, it would be recommended to install unseating prevention devices on all bridges.

(a) Gaps caused by transverse displacement of 2-way bridges

(b) Damages to drainage pipelines caused by excessive displacement of bridge decks

(c) Damages caused by excessive displacement of bridge bearings

(d) Bridge damage inspection process

Figure 3.1 Bridge damage investigations for Bridge No. 24 of Provincial Highway 86

IV. On-site assessment for seismic damage - Land subsidence and liquefaction

4.1 Preliminary results of the geotechnical works disaster surveillance

The following summarizes the outcomes of the post-earthquake geotechnical works disaster investigation conducted by the NCREE with regard to the sinking and tipping of streets, houses, and buildings as well as damages experienced by the embankments of Zengwun River:

(A) Areas around Alley 10, Lane 50, Sanmin Street, Sinshih District, Tainan City

Soil liquefaction caused many houses in the area around Lane 50, Lane 50 Alley 10, and Lane 10 of Sanmin Street (an area about 60 m x 60 m in size) to sink or tip (Figure 4.1A). On-site measurements showed that sand eruption resulting from the liquefaction reached as high as 150 cm (Figure 4.1B). Sinking depths for the ground level floors in the building was about 47 cm compared to the street level (Figure 4.1C). Sand eruptions were also observed from drainage sewer manhole covers, utility poles, fire lanes, and drains around the building areas. For this area, damages were observed for the garage shed and fences built in front of the ground floor door as well as sinking and slight tipping of the main building. No other visible structural damage was seen. No other signs of disaster were observed outside this area, including buildings opposite the street of Lane 50 and Lane 10 of Sanmin District. After interviewing local residents and reviewing maps of Taiwan 100 years ago provided by Academia Sinica, it was found that this area was once a pond that was later filled to create land. Hence, only severe liquefaction was observed in this area but none in the vicinity.

(B) Areas around Xiding Village, Annan District, Tainan City

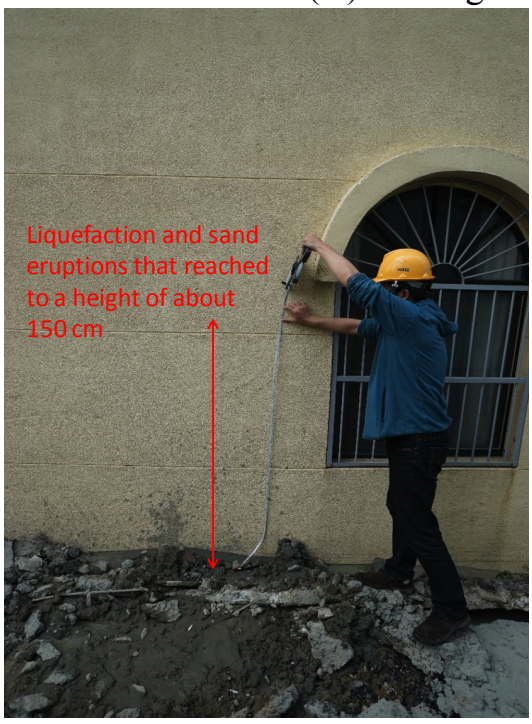
Xiding Village, Annan District, Tainan City was located to the north of Old Tainan City and was sandwiched between the southern bank of the Chianan

Irrigation drainage line, the eastern side of Section 2 of Bei'an Road, and northern bank of Yanshui River. This area experienced severe liquefaction during the earthquake, especially in the area from Hui'an Street to Section 4 of Fu'an Road, with signs of eruptions from drains, manhole covers, and bottom of utility poles. Building tipping or sinking caused by soil liquefaction was most evident in Lane 161 of Hui'an Street. The building located at No. 24, Lane 161, Hui'an Street (Figure 4.2A) sank and tipped towards the rear by about 5 degrees as a result of soil liquefaction. The building located at No. 8, Lane 161, Hui'an Street sank by nearly half a story due to liquefaction (Figure 4.2B). On-site measurements showed that this forward tipping angle of the building reached 4 degrees (Figure 4.2C). It was determined that the local stratum may be relatively weak due to its proximity with Yanshui River. Century-old maps from Academia Sinica also revealed that the region around Xiding Village used to be a pond, and was thus severely affected during this earthquake.

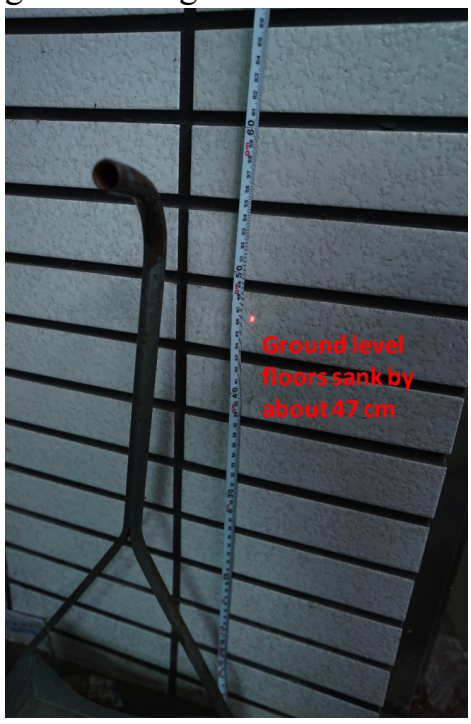
(C) Lateral spreading and damages to the embankments of Zengwun River

This earthquake caused large scale lateral spreading damages of Rixin embankments at Danei Bridge of Zengwun River in Tainan District (Figure 4.3) and right side levees at the Freeway No. 3 connection of Zengwun River Bridge (Figure 4.4). Cracking of concrete bank protection as well as warping and sinking of the levee road were also observed for the levees on the right bank of Erxi Bridge. Large amounts of sand due to soil liquefaction were also observed at locations where bank protection used to be at the lateral spreading spots of the Zengwun River levees. NCREE personnel also collected samples from these places (Figure 4.5) for subsequent laboratory testing.

(A) Sinking and tipping of buildings



(B) Liquefaction and sand eruptions that reached to a height of about 150 cm

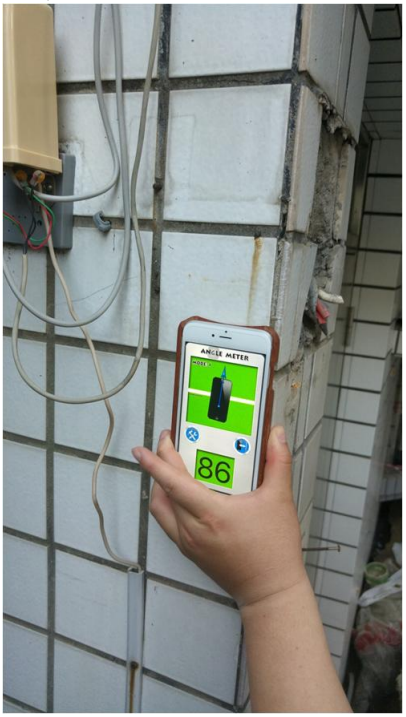


(C) Ground level floors sank by about 47 cm

Figure 4.1 Building tipping and sinking due to soil liquefaction at Alley 10, Lane 50, Sanmin Street, Sinshih District, Tainan City (provided by Chia-Han Chen)

(A) Building at No. 24, Lane 161, Hui'an Street

(A) Building at No. 8, Lane 161, Hui'an Street



(C) Measuring the tipping angle in front of the house

Figure 4.2 Building tipping and sinking due to soil liquefaction at Lane 161, Hui'an Street, Annan District, Tainan City (provided by Shang-Yi Hsu)

Figure 4.3 Supporting companies conducting digital topographic scanning and mapping at the lateral spreading site of Rixin embankments (provided by Shang-Yi Hsu)

Figure 4.4 Lateral spreading damages at the embankments of Zengwun River Bridge at Freeway No. 3 (provided by Shang-Yi Hsu)

Figure 4.5 Collecting samples of liquefied soil at the lateral spreading site of Zengwun River embankments (provided by Hsuan-Chih Yang)

4.2 Lessons learned and recommendations from the geotechnical works disaster survey

Outcomes from the preliminary geotechnical works disaster survey revealed no damages to the structure and columns of buildings that tipped or sank due to liquefaction. Very few cracks were also observed on the 2nd and 3rd floor wall surfaces (as shown in Figure 4.1A and Figure 4.1B). However, the weight and load of the building caused the main structure to settle more as well as differential settlements of other accessory structures (such as fences of the front yard, garage doors, and shades) and pipeline connections at the ground floor, damaging these accessory structures and utility pipelines (as shown in Figure 4.1A).

Geotechnical disasters caused by major earthquakes such as regional liquefaction or subsidence as well as lateral spreading of embankments or sliding of slopes tend to cover large areas and result in extensive damages. Some of these damages were located in relatively inaccessible areas. Remote-controlled aerial photography is the key in fulfilling comprehensive and real-time assessment requirements needed for this type of geotechnical disaster inspection (Figure 4.6). It can provide the real-time evidence and establish a basis for on-site disaster inspection for determining the extent of damage.

Figure 4.6 Setting up aerial photography tools for Sanmin Street, Sinshih District during this field survey (provided by Wei-Kuang Chang)

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