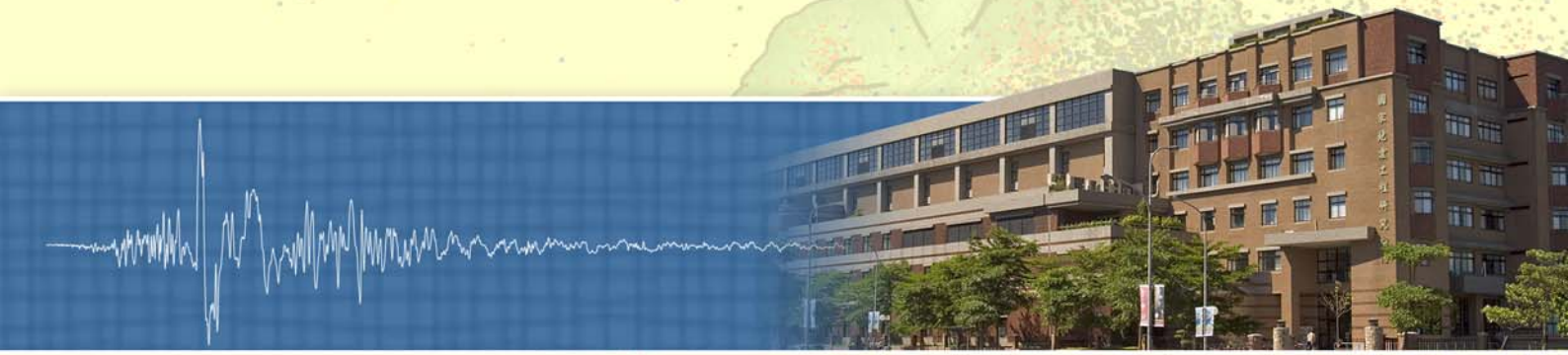
NCREE NEWSLETTER

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SPECIAL ISSUE



February 6, 2016 Meinong Kaohsiung Earthquake and Lessons Learned

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National Center for Research on Earthquake Engineering

Special Issue: February 6, 2016 Meinong Kaohsiung Earthquake and Lessons Learned

NCREE Earthquake Emergency Response Procedure

Fang-Yao Yeh, Research Fellow, and Chiun-lin Wu, Associate Researcher

Introduction

This issue of the newsletter presents the NCREE emergency response procedure for the 2016 M_L-6.6 Meinong earthquake as an illustrative example, and reports findings from a reconnaissance of the damage to buildings, nonstructural components and systems, geotechnical structures, *etc*., to be shared with industrial, governmental, academic, and research communities.

Mobilization of Response to Meinong Earthquake

The M_L-6.6 Meinong earthquake hit at 3:57 am, and later, at 4:05 am, TELES issued a short cellphone message to broadcast its early-stage estimate of twelve casualties (with a possible range of five to thirty) and that more than 1,000 villages should remain on alert. As per the NCREE's emergency mobilization standard, the earthquake emergency response procedure was then activated. At 4:59 am, the Central Emergency Operation Center (CEOC) of the Executive Yuan sent a cellphone message to request that its personnel and collaborating emergency response units be immediately stationed at the Center. In response to this request, the NCREE dispatched its leading staff member in the Earthquake Emergency Decision Making Task Group, Dr. Juin-Fu Chai, to respond to the mobilization request.

After the Earthquake Loss Assessment Task Group and the Damage Information Collection/Compilation Task Group were stationed at NCREE, the Meinong Earthquake Report v1.0 was released at 7:16 am on February 6 to present a summary of the earthquake event, covering the shaking intensity distribution, PGA distribution and acceleration waveforms observed from the Central Weather Bureau (CWB) and NCREE real-time seismic networks, focal mechanism solutions, activities of aftershocks, historical earthquakes in the vicinity of the Meinong earthquake epicenter, TELES-estimated PGA and spectral acceleration distribution maps, TELES-estimated casualties, TELES-estimated building damage, earthquake damage reported in the media, *etc*. The above compiled information was then provided to the NCREE's Earthquake Emergency Decision Making Task Group and the CEOC of the Executive Yuan. The Meinong Earthquake Report v2.0 was released at 8:51 am with an update on the ground motion distribution maps, recorded acceleration time histories, and their acceleration spectra. The Meinong Earthquake Report v3.0 was released at 9:58 am with an update on the damage to buildings, schools, and highways. The Meinong Earthquake Report v4.0 was released at 11:51 am with an addition of major disasters and estimated PGAs at schools. The Meinong Earthquake Report v5.0 was released at 12:18 am two days later on February 8 with an update on ground motion information and a report on damage to schools. Subsequent updates to the earthquake reports reflected further damage information collected to become a timely reference portfolio for the NCREE's Earthquake Emergency Decision Making Task Group and the CEOC of the Executive Yuan. The CEOC was dismissed at 4:00 pm on February 14. The NCREE task groups were also dismissed, and personnel resumed their original duties accordingly.

As the Meinong earthquake struck one day before the Lunar New Year's Eve, many NCREE employees had already gone back to their hometowns and prepared for national holidays. In addition, severe damage to the Taiwan High Speed Rail further impaired timely mobilization of the original emergency shift roster. After discussions with Deputy Director Chien-Chih Hsu, the emergency response procedure switched to the "nearest recruitment" mode, which mobilized personnel who still remained in the Taipei metropolitan area to conduct the emergency response. The NCREE also requested Professor George C. Yao of National Cheng Kung University to coordinate a response team to conduct reconnaissance investigations during the Lunar New Year vacation. The NCREE also mobilized its personnel who were already in southern Taiwan and collaborating institutes to conduct reconnaissance investigations during the Lunar New Year vacation. During the emergency response procedure, telecommunications (landline, cellphone, email, *etc*.) were the main tools NCREE utilized to mobilize its task groups.

Characteristics of Source and Strong Motion of the Meinong Earthquake

Chun-Hsiang Kuo, Che-Min Lin, Associate Researcher, and Yu-Wen Chang, Hung-Hao Hsieh, Assistant Researcher
Kuo-Liang Wen, Division Director, Professor, Central University, Wen-Yu Chien, Research Fellow

Introduction

On February 6, 2016, at 03:57:26.1 CST (February 5, 19:57:26.1 UTC), an earthquake with a local magnitude (M_L) of 6.6 occurred in the Meinong District of Kaohsiung City in southern Taiwan. The epicenter was located at 120.54 E and 22.92 N, approximately 27.1 km northeast of the Pintung County Hall, according to the latest report released by the Central Weather Bureau (CWB). The original report announced that the earthquake had occurred at 03:57:27.2 CST, was located at 120.54 E and 22.93 N, and had a local magnitude of 6.4. After collecting more data, the CWB announced an updated report in which the magnitude was revised to 6.6, the epicenter was slightly shifted, the focal depth was changed from 16.7 km to 14.6 km, and the occurrence time was also changed to a slightly earlier time (Fig. 1). The U.S. Geological Survey (USGS) gave the moment magnitude (M_W) as 6.4, the epicenter location as 120.601 E and 22.938 N, and the focal depth as 23 km.

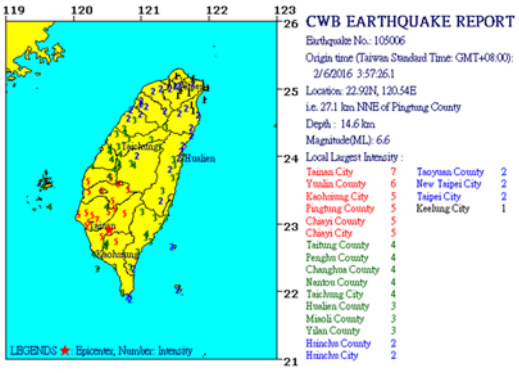


Fig. 1. The latest CWB report for the 0206 Meinong earthquake

Source Characteristic

The focal mechanisms calculated by the CWB and the USGS are slightly different from each other (Fig. 2). The CWB calculated the focal mechanism using a centroid moment tensor solution from broadband seismic data. The strike/dip/rake of the two obtained nodal planes are 274.81/41.47/17.02 and 171.95/78.76/130.47, indicating left-lateral strike-slip and reverse-oblique source characteristics, respectively. The USGS announced five different mechanisms calculated using different methods. The optimum one is the W-phase moment tensor solution, which used the most data and has a strike/dip/rake of 299/25/38 and 174/75/110, indicating reverse-oblique and reverse source characteristics, respectively. At present, seismologists believe the true focal plane was 274.81/41.47/17.02, according to the distribution of aftershocks, and thus the other nodal plane is the conjugated plane.

After the mainshock occurred, many aftershocks occurred, but inside Tainan City. The region surrounding the mainshock experienced no obvious aftershocks. An aftershock of magnitude 4.3 occurred in this region on February 8. Otherwise, the focal depths of the aftershocks in Kaohsiung City were mostly less than 20 km; however, the aftershocks in Tainan City were between 20 km and 30 km. The catalog of aftershocks until March 10 was downloaded from the Geophysical Database Management System (GDMS) of the CWB and the distributions of different magnitude aftershocks were plotted as in Fig. 3. The aftershocks were mainly distributed in the epicenter region (Kaohsiung City), the western region (Tainan City), and the eastern region (Taitung County). In addition, there was also a linear distribution of aftershocks to the north of the epicenter. Because seismic data on the strong ground motions was not released, many significant characteristics were still not very clear until now.

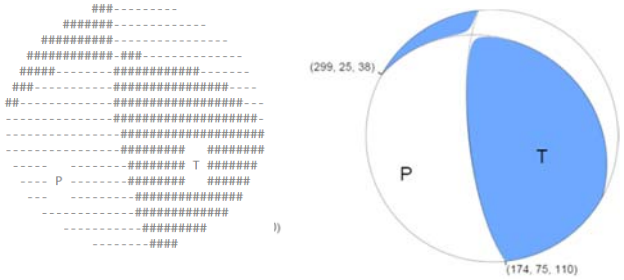


Fig. 2. The focal mechanisms from the CWB (left) and the USGS (right)

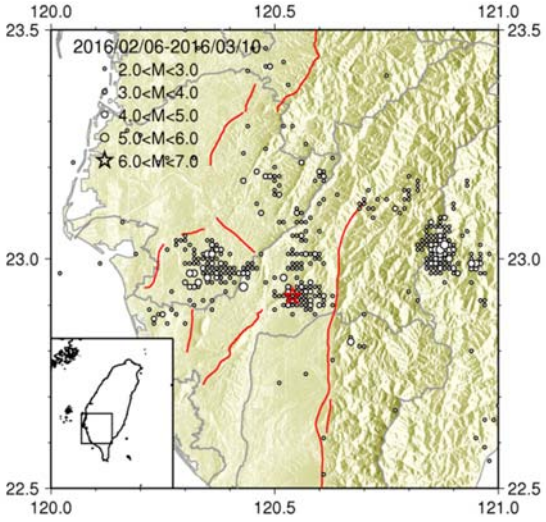


Fig. 3. Distribution of aftershocks until March 10

Ground Motion Characteristic

The CHN5 station recorded the largest PGA of 344.12 gal (intensity 6, with PGAs of 250–400 gal) at an epicentral distance of 76 km according to the rapid report of the CWB. The intensity at the CHN3 station was

modified to 7 (PGA of 401.19 gal) at an epicentral distance of 25 km; otherwise, the NCREE's A730 station recorded a PGA of 408.01 gal, which also corresponded to intensity 7 (PGA larger than 400 gal). Several NCREE stations in the Taipei region also observed intensity 1, which is also identical to that of the CWB's stations.

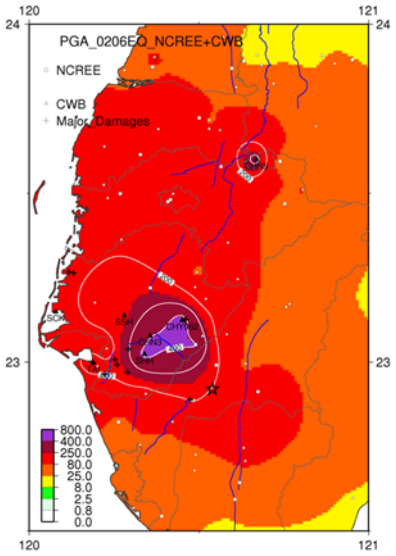


Fig. 4. A PGA shake-map of the Meinong earthquake

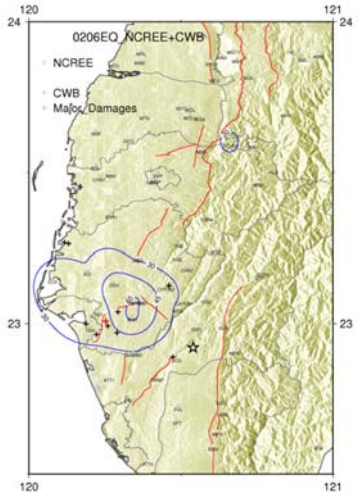


Fig. 5. A PGV shake-map of the Meinong earthquake

This report used the data from the real-time stations of the CWB and the strong-motion network and EEW stations of the NCREE to construct a shake-map for the near-source region of the mainshock (Fig. 4). Intensities are plotted as different colors and the region with intensities larger than 200 gal is plotted as white isoseismals with an interval of 100 gal. The cities exposed to intensities 6 and 7 were Kaohsiung and Tainan, located northwest of the epicenter, which suffered from an obvious forward-directivity rupture effect. In contrast to the direction, the PGA is much weaker and the attenuation is faster.

The integrated PGV map is shown in Fig. 5. The regions that have a PGV larger than 30 cm/s are plotted as blue isoseismals with an interval of 15 cm/s. The south Tainan region was exposed to an intensity of PGVs larger than 30 cm/s, while the intensity near the CHN3 station was as large as 60 cm/s. However, the epicenter was not inside the isoseismals. We suppose this is due to the lack of stations between the epicenter and the CHN3 station. A shake-map of higher resolution may be constructed after the seismic data of free-field strong motion stations are released by the CWB. However, we can see that the major damages (marked as black crosses) are mostly located in the region exposed to PGAs larger than 200 gal and PGVs larger than 30 cm/s in Fig. 4 and Fig. 5.

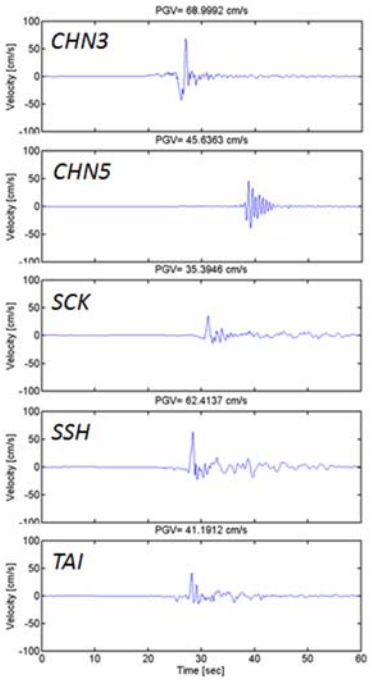


Fig. 6. The observed pulse-like velocities during the Meinong Earthquake

The strong effect of the forward-directivity rupture was obviously recorded in the seismic data of the mainshock. According to previous studies, pulse-like velocities can usually be observed in such an earthquake with a magnitude greater than 6 and the seismic signal typically has a higher PGV at a longer period. This kind of seismic signal is believed to be a major characteristic of near-fault strong motions, which are able to cause significant damage to nearby structures. Seismic data of intensities larger than 5 were analyzed in the report. Pulse-like velocities were determined at five stations and the PGV of the largest horizontal component was larger than 30 cm/s at all stations. The S-wave also exhibited longer periods at those stations. The CHN5 station has an abnormal velocity waveform that is also different from those at the other stations. This station recorded a PGA of more than 300 gal at a large distance of 70 km. We therefore suppose it might be an effect of topography.

The detailed shake-maps in Fig. 7 show the ground motion intensity of the Taiwan area resulting from the Meinong Earthquake. The short-period spectral acceleration (S_{as}) and the 1-second spectral acceleration (S_{a1}) reveal large seismic demand on structures in Tainan City. Several buildings in Tainan City were damaged by the earthquake. As shown in Fig. 8, the acceleration response spectra of the four stations and the seismic requirements for their location in the seismic building code are compared. The four stations recorded PGAs of

more than 200 gal during the earthquake. Based on the current seismic structural design code, the design basis earthquake for short-period spectral acceleration (475 years return period) is 0.7–0.8 g for Tainan city. Therefore, damage to structures can be expected.

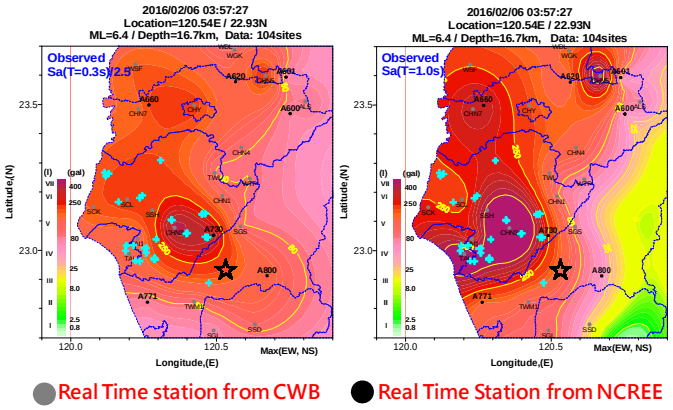


Fig. 7. Shake-maps of short-period spectral acceleration (T = 0.3 s) and 1-second spectral acceleration of the Meinong Earthquake

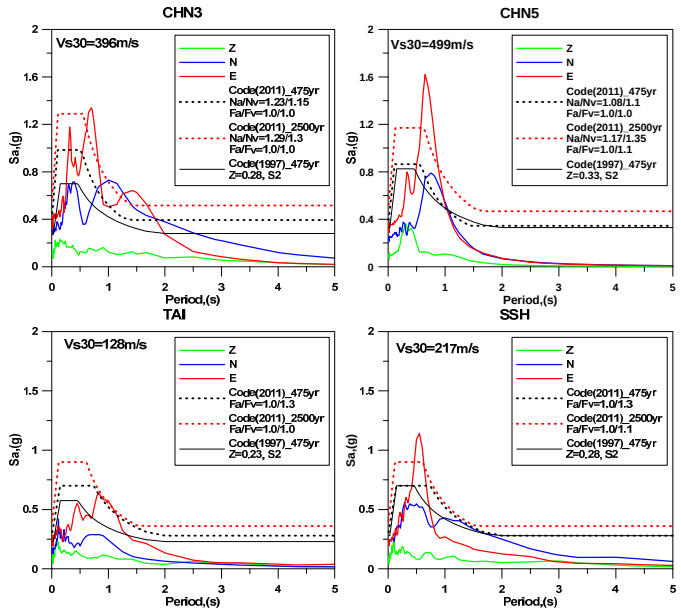


Fig. 8. Acceleration response spectra of four stations and the seismic requirement for their location in the seismic building code

Comparison of Historical Earthquakes

Taiwan is the location that experiences frequent seismicity, and five events (including the Meinong Earthquake) with magnitudes larger than $M_L = 6.0$ have occurred in southern and central Taiwan over the past ten years. In particular, the March 4, 2010, M_L6.4 Jiasian Earthquake had an epicenter located ~20 km from that of the Meinong Earthquake. A comparison of the acceleration response spectra of three historical earthquakes at the TAI1 station located in Tainan City is shown in Fig. 9. Table 1 lists the source parameters of the three historical earthquakes and their PGA values at the TAI1 station. The orientations between the station and the epicenter may reveal the directionality effect causes of the source mechanisms. The rupture characteristic of the source of the Meinong Earthquake clearly induces the long-period wave at this station.

Table 1 PGA values at the TAI1 station during three historical earthquakes

Earthquake (local time)	Source Parameter	PGA	Epicenteral Distance(km)
1999/09/21	M_L7.3 Focal Depth=8km	88 gal	108
2010/03/04	M_L6.4 Focal Depth=22.6km	104 gal	52
2016/02/06	M_L6.4 Focal Depth=16.7km	148 gal	33

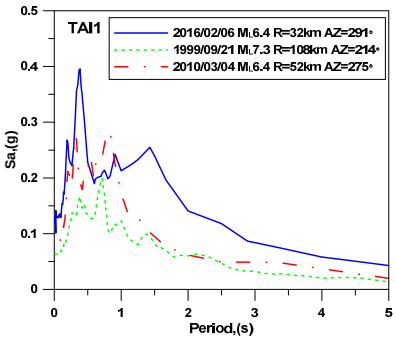


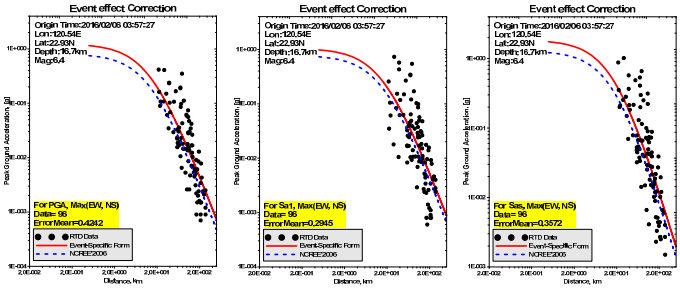
Fig. 9. Comparison of acceleration response spectra of three historical earthquakes at the TAI1 station

Ground Motion Prediction

To provide reliable ground motion predictions when an earthquake occurs, a hybrid procedure that combines a site-dependent ground motion prediction model and the limited observations of a real-time digital (RTD) stream output system (an RTD system operated by the CWB) provides a near-real-time shake-map. The former is a site- and intensity-dependent ground motion prediction model (for the attenuation relationship) that considers the source effect and/or the location uncertainty in a particular earthquake. The observed data from the latter can be used to correct the systematic bias that exists between the reference ground motion prediction model and the event characteristics, and can replace its estimated value in the shake-map to improve the reliability.

As shown in Fig. 10, a systematic bias exists between the observed data from the RTD stations during the Meinong Earthquake and the reference ground motion prediction model. The red line is the event-dependent ground motion prediction model after removing the systematic bias from the observed data. According to previous studies, the intensity value of each CWB station can be estimated from the event-dependent ground motion prediction model in association with a function for its site amplification factor. Using a hybrid procedure in which the records are used to replace the estimated result of the CWB station provides a high-quality shake-map. Fig. 11 shows a PGA shake-map of the Tainan area developed using the hybrid procedure. The map was constructed by including 160 TSMIP stations, 24 RTD stations, and seven real-time stations of the NCREE. The forward-directivity rupture effect due to

the Meinong Earthquake appears very clearly on the predicted PGA shake-map in Fig. 11. The hybrid procedure can thus provide a high-quality shake-map to efficiently plan an investigation scheme for probable damage when an earthquake occurs.



ig. 10. Comparison between the reference ground motion prediction model and the observed data of the Meinong Earthquake

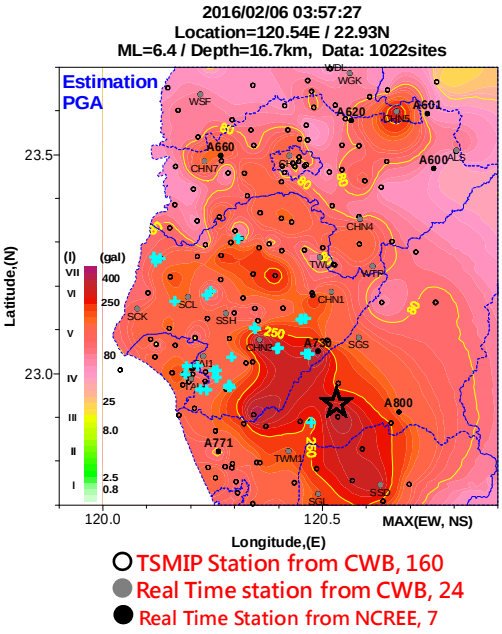


Fig. 11. A predicted PGA shake-map for the Meinong Earthquake

5th IASPEI / IAEE International Symposium: Effects of Surface Geology on Seismic Motion

We are pleased to announce that, this year, the 5th International Symposium on the Effects of Surface Geology on Seismic Motion (ESG5) will be hosted on August 15–17, 2016, in the Taipei International Convention Center (TICC), Taiwan. The symposium is hosted by the National Center for Research on Earthquake Engineering, Taiwan (NCREE) and will be attended by over 200 conferees.

Main topic of the symposium:

Challenges of Applying Ground-Motion Simulation to Earthquake Engineering

Symposium Topics:

1. Ground-Motion Simulation
2. Shallow Velocity Structure and Depth Parameters
3. Soil Dynamics and Nonlinearity
4. Applications of Microtremor Surveys
5. Downhole Array Observation and Analysis
6. Near-Fault Ground Motion
7. Seismic Hazard and Loss Assessment
8. Other Site Effect Studies

The program of ESG5 includes not only eight keynote speeches and several invited speakers for parallel sessions but also some poster sessions that have been arranged for all participants to promote and exchange their ideas.

Considering the seriousness of a near-fault seismic disaster, the NCREE's new laboratory is establishing a new long-stroke high-velocity shaking table system to develop near-fault seismic resistance technology. On the last day of the symposium, the NCREE will introduce the new system to conferees and exchange ideas with participants for future research plans.

For further information, please visit the ESG5 website: esg5.ncree.org.tw

(Jyun-Yan Huang, Assistant Researcher)

Application of Early Seismic Loss Estimation in Emergency

Chin-Hsun Yeh, Division Director, and Lee-Huei Huang, Assistant Researcher

Compared with other natural disasters, the occurrence time and location of an earthquake are difficult to forecast. After an earthquake, the emergency response bodies in a government or enterprise should have reliable information for predicting the severity of a disaster caused by the earthquake, and they should decide whether to initiate an Emergency Operation Center (EOC) in order to save time and to reduce casualties and property losses. Once the EOC is initiated, it is also necessary to predict probable disaster distribution for dispatching rescue, medical, and livelihood resources. In particular, isolated disaster-affected regions may exist and should be identified as soon as possible in order to prevent delay in rescue operations that may result from disruption of electricity, communication, or transportation.

To avoid inadequate interpolation of peak ground acceleration (PGA) and to avoid difficulties in obtaining accurate seismic source parameters soon after a strong earthquake, the National Center for Research on Earthquake Engineering (NCREE) developed early seismic loss estimation (ESLE) techniques. The methodology of ESLE is briefly explained as follows. A scenario simulation database is built prior to the occurrence of an earthquake. The scenario database contains simulation results of thousands of earthquakes, which represent all possible earthquakes in the future. When a strong earthquake occurs, the ESLE system will be automatically triggered when it receives an earthquake alert email from the Central Weather Bureau (CWB). Several scenarios are selected by matching the simulated PGA and the observed PGA at the CWB rapid stations. Since the source parameters of the selected scenarios are close to the observed source characteristics, and the ground-motion intensity patterns are similar to each other, it can be reasonably assumed that the predicted damages and losses using the selected scenarios will be close to the actual cases. Therefore, in some sense, the ESLE technique adopts every piece of information contained in the earthquake alert email from the CWB.

The application of ESLE after an earthquake occurrence may be divided into three stages:

(1) First stage: within two minutes after receiving an earthquake alert email from the CWB. The system can automatically start and complete assessment of probable disasters within two minutes. Emergency response personnel will be notified with a simple text message, email, or through other media. The content of the simple text message is customized to fit individual needs and contains information on the predicted severity of the disaster, which may be used to decide whether it is necessary to start an EOC as soon as possible in order to improve rescue time.

(2) Second stage: within six hours after earthquake occurrence. Combining information about the acceleration time histories at the CWB rapid stations, the fault plane solutions provided by the USGS and/or the CWB, and the distribution of aftershocks, several probable sets of seismic source parameters may be proposed and justified by running scenario simulations. Based on the simulation results, the most probable scenario can be identified and used to prevent an isolated disaster-affected location from being overlooked.

(3) Third stage: within one month after the earthquake. The earthquake loss estimation model and the associated parameter values should be reviewed by comparing the entire actual disaster and the estimated ones in order to ensure the credibility of disaster planning and risk management, which used the same loss estimation model.

ESLE First Stage

One minute after receiving the CWB earthquake alert, the ESLE completed the disaster estimation and sent simple text messages to notify emergency response personnel. The content of the simple text message for the Meinong earthquake (Fig. 1) indicated the probable number of casualties as between 5 and 30 with a best estimate of 12; the residential earthquake insurance losses as between NT$179 and NT$546 million with a best estimate of NT$529 million; the number of repairs to water pipelines needed as around 1432 and concentrated in the Tainan area; and that there were more than one thousand villages (1045) with PGAs greater than 160 gal. Because of the severity of the disasters that may have been caused by the Meinong earthquake, it was recommended to partially initiate emergency responses. Other more detailed information could be found in the e-mail or through the website.



Fig. 1. Customized simple text messages in the ESLE first stage

Six scenarios (Fig. 2) that may represent the Meinong earthquake were selected by ESLE in the first stage. Thematic maps such as PGA, spectral accelerations at various structural periods, building damage, and human casualties were also generated automatically to enable a quick grasp of the distribution of disasters. According to ESLE in the first stage, the ground shaking intensity was larger in a direction northwest of the epicenter, the most serious casualties occurred in Tainan, and the building damages were concentrated in Yongkang District. Compared with the survey results, although the ESLE was completed automatically within a very short time, both the severity and distribution of disasters were captured.



Fig. 2. Six scenarios selected by ELSE

ESLE Second Stage

Reliable source parameters are indispensable for making accurate loss estimations. Hence, the second stage of ESLE focuses on obtaining reasonable source parameters, which will be inputted into the Taiwan Earthquake Loss Estimation System (TELES). The acceleration time histories at the CWB rapid stations are downloaded and analyzed soon after the earthquake in order to understand the characteristics of ground motion in different districts. It is found that the vibration in the east–west direction was greater than that in the north–south direction. Some of the waveforms exhibit a significant velocity pulse. Around one hour after the earthquake, the fault plane solutions were released by the US Geological Survey (USGS) and the CWB. Integrating the previous information and the distribution of aftershocks within three hours (Fig. 3), the seismic source parameters were judged to be as follows: the fault strike had an approximately east–west orientation, the fault plane was slightly north-dipping, the fault rupture had a left-slip component, and the directivity effect was significant. In summary, the input source parameters in the ESLE second stage were set to magnitude 6.4, focal depth 15 km, strike west 20° to the north, and rupture length 20 km. It is noted that the rupture fault-line assumed in the ESLE second stage (Fig. 3) starts from the epicenter of the Meinong earthquake to reflect the observed directivity effect.

Review of ESLE Accuracy

Comparing the ESLE results with the results of actual disasters determined through reconnaissance (Table 1), it was found that the number of building damages and the amount of residential earthquake insurance payout had been well estimated; that is, the actual value was likely to fall within a range bounded by one-half and two-times the estimated value. However, there existed a large discrepancy between the estimated casualties and the actual casualties. The number of casualties in the Weiguan Jinlong high-rise building was 115, which was far beyond the expected casualty rate. Nonetheless, it was only a single case. In TELES, the casualty assessment model takes into account the damage state probability of model buildings, the probable population inside buildings, and the casualty rate due to building damages. On average, the injury and casualty rates due to building collapse should not be so large. Therefore, there is no need, thus far, to modify the parameter value used in casualty assessment.



Fig. 3. Aftershocks within three hours (red dashed lines are faults in the first and second stages)

Table 1. Comparison of actual disasters and estimates

	Building damage			Casualty	Insurance loss (million)
	1-7 floor	>8 floor	total		
Actual	236	10	246	117	>145
First stage	348	9	357	12	528
Second stage	210	6	216	6	252

Concluding Remarks

The TELES developed by the NCREE can be used to propose disaster reduction plans and risk management strategies through a scenario-based approach, which are useful in reducing structural damage, human casualties, and/or economic losses. The ESLE, a subsystem of TELES, may be used to enhance the efficiency of emergency response and to verify the accuracy of earthquake loss estimation models. In other words, the ESLE can and should be used to verify the validity of disaster reduction plans and risk management strategies.

Performance of On-site EEW System during the Meinong Earthquake

Ting-Yu Hsu, Pei-Yang Lin, Research Fellow, Hsui-Hsien Wang, Research Assistant
Shieh-Kung Huang, Hung-Wei Chiang, Kung-Chun Lu, Assistant Researcher

As Taiwan suffers from seismic hazards that occur in-land, the lead time given by a regional EEW system before the arrival of a destructive earthquake wave can be zero. Therefore, the National Center for Research on Earthquake Engineering (NCREE) has been developing an on-site EEW system since 2009 in order to provide more lead time in a region with greater potential damage and loss, *i.e.*, the region close to an epicenter. The on-site EEW system predicts the peak ground acceleration (PGA) of an incoming earthquake at a station through the use of an artificial intelligence technique (Hsu *et al.*, 2013, doi:10.1016/j.soildyn.2013.03.001). The system will issue an alarm if the predicted intensity is higher than a pre-assigned threshold using earthquake features extracted from the first three seconds of the seismic P-wave measured at the same station after the system is triggered by an earthquake.

Based on the experience of seismic reconnaissance in Taiwan, a region with a seismic intensity level of 5 or greater (on the Shindo scale), *i.e.*, PGA > 80 gal, could suffer structural damage, while a region with a seismic intensity level of 4 or greater, *i.e.*, PGA > 25 gal, could suffer minor damage such as falling objects. Another concern is that people in eastern Taiwan (Yilan County, Hualien County, and Taitung County) will be exposed to a greater earthquake hazard than those in western Taiwan. Therefore, the threshold to issue an alarm for EEW stations in eastern Taiwan is set to seismic intensity level 5, while those in western Taiwan are set to seismic intensity level 4.

During the Meinong earthquake that occurred on February 26, 2016, the acceleration time history was recorded at a total of sixteen EEW stations. Although earthquake alarms were immediately issued successfully at these stations, no warnings were broadcast in schools since the earthquake occurred before dawn. The locations of these sixteen stations are plotted on a map of Taiwan against the PGA distribution (Figure 1). The PGA is calculated using data collected from the Real-Time Digital (RTD) stream output system operated by the Central Weather Bureau (CWB) and from the Real-Time Seismic (NRTS) stations and EEW stations operated by the NCREE.

First, the accuracy of the predicted PGA during the Meinong earthquake is considered. The predicted PGAs and the measured PGAs of all sixteen stations are plotted in Figure 2. It can be observed that the predicted PGAs correspond to the measured PGAs very well on a logarithmic scale. The standard deviation of the differences between the predicted PGAs and the measured PGAs is approximately 40.8 gal. Regarding the difference in the seismic intensity levels that are used as a basis to issue an alarm for general applications, as shown in the same figure, the intensity differences between all stations are within a range of plus one level or minus one level, except at the S12 station. The measured PGA at the S12 station was 8.8 gal, which is just above the threshold of the third seismic intensity level, *i.e.*, 8 gal, while the predicted seismic intensity was level 1. However, since the measured seismic intensity was smaller than the threshold to issue an alarm, this under-estimated intensity did not in practice affect the results.

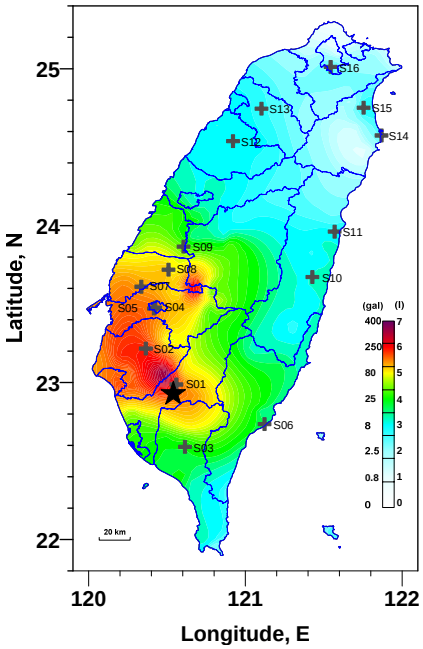


Fig. 1. The location of on-site EEW stations

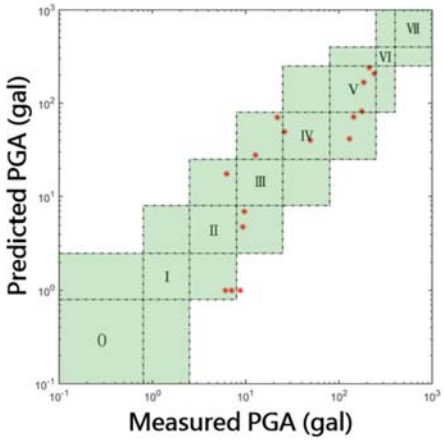


Fig. 2. The distribution of measured PGA and predicted PGA for sixteen on-site EEW stations

Regarding the accuracy of issued alarms, the four alarm conditions are defined as follows: (1) Correct Alarm (CA), when both the measured and the predicted intensities reach the alarm threshold; (2) Correct No Alarm (CNA), when both the measured and the predicted intensities are smaller than the alarm threshold; (3) Missed Alarm (MA), when the measured intensity reaches the alarm threshold but the predicted intensity is smaller than the alarm threshold; and (4) False Alarm (FA), when the measured intensity is smaller than the alarm threshold but the predicted intensity reaches the alarm threshold. In the Meinong earthquake, according to the pre-assigned thresholds at each station, eight stations were classified as CA and eight stations were classified as CAN. In other words, the alarm conditions of all sixteen stations were correct (see Table 1).

Table 1. Stations in NCREE's on-site EEW system and their performance summary during the Meinong earthquake

No.	Epicenter Distance (km)	Lead-Time (sec)	Measured PGA (gal)	Predicted PGA (gal)	Measured Intensity	Predicted Intensity	Alarm Threshold	Alarm Status
S01	7	3.8	213.3	240.3	5	5	4	CA
S02	36	8.4	242.0	207.4	5	5	4	CA
S03	38	6.9	26.2	49.6	4	4	4	CA
S04	60	10.4	184.3	167.7	5	5	4	CA
S05	62	10.4	175.8	81.8	5	5	4	CA
S06	64	5.4	22.0	70.7	3	4	5	CNA
S07	77	12.6	144.2	70.8	5	4	4	CA
S08	85	12.8	130.8	41.3	5	4	4	CA
S09	104	17.0	49.4	40.2	4	4	4	CA
S10	122	20.0	12.8	27.9	3	4	5	CNA
S11	155	23.1	9.7	6.9	3	2	5	CNA
S12	183	23.5	8.8	1.0	3	1	4	CNA
S13	208	32.8	7.1	1.0	2	1	4	CNA
S14	226	29.0	6.1	1.0	2	1	5	CNA
S15	235	19.9	9.3	4.8	3	2	5	CNA
S16	252	4.7	6.3	17.4	2	3	4	CNA

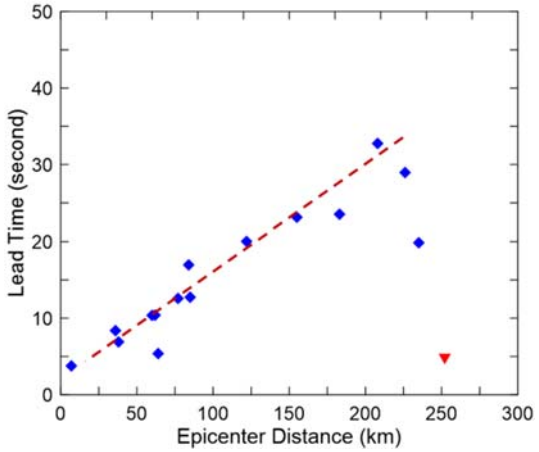


Fig. 3. Lead time and epicentral distance (the red triangle represents the S16 station)

Regarding the lead time gained by the on-site EEW systems, the lead time is defined as the time interval between the time an alarm is issued and the time of arrival of PGA. By observing the relationship between the lead time and the epicentral distance shown in Figure 3 and Table 1 for the Meinong earthquake, it is evident that in general the lead time increases as the epicentral distance increases. At the S01 station with an epicentral distance of only 7 km, the lead time is approximately 3.8 seconds (Figure 4). At the S02 station, which is close to the region suffering serious damage (with an approximately 36-km epicentral distance), the lead time is approximately 8.4 seconds (Figure 5). Other regions with seismic intensity level 5 also receive around 10–13 seconds of lead time (*e.g.*, S04 station in Figure 6). Theoretically, the farthest station should receive the longest lead time. However, the S16 station, which had the longest epicentral distance, only received 4.7 seconds of lead time. This is probably due to a poor signal-to-noise ratio at that station. That is, the P-wave is too small to trigger the system until the arrival of the S-wave with larger amplitude (Figure 7). Fortunately, in practice, since the seismic intensity at stations with a low signal-to-noise ratio is generally not sufficiently large to issue an alarm, no negative effects will ensue.

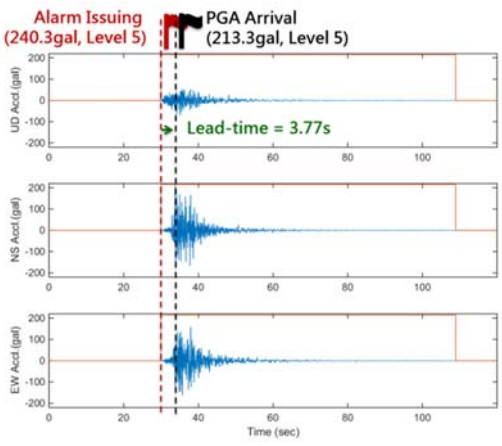


Fig. 4. Measured acceleration time history and alarm issued at the S01 station

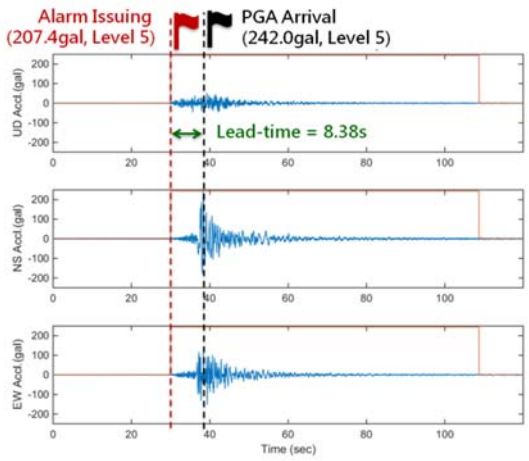


Fig. 5. Measured acceleration time histories and alarm issued at the S02 station

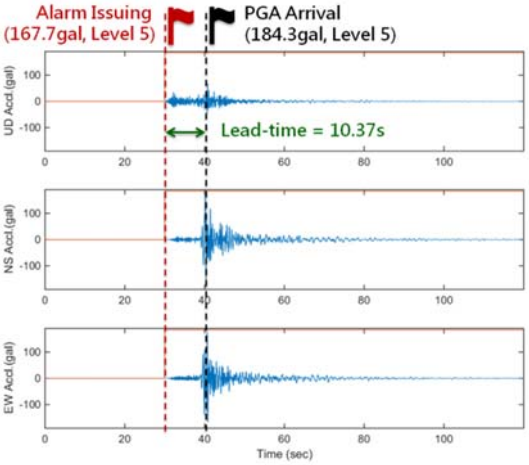


Fig. 6. Measured acceleration time histories and alarm issued at the S04 station

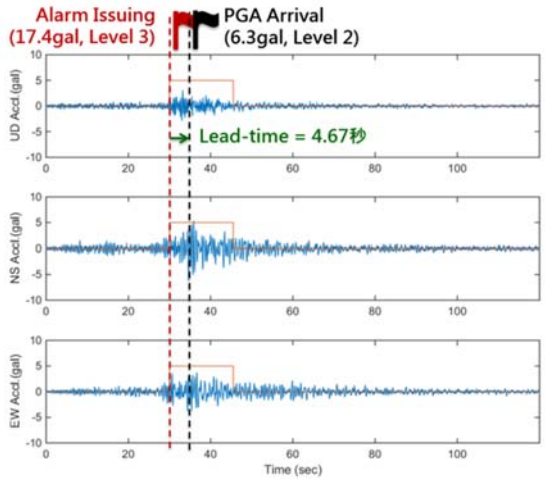


Fig. 7. Measured acceleration time histories and alarm issued at the S16 station

It is worth mentioning that, for a region with a measured intensity level equal to or greater than 5 for the Meinong earthquake, the lead time provided by an on-site EEW system is approximately 4–13 seconds and the accuracy of the alarm being issued is 100%. It is clear that the on-site EEW systems developed by the NCREE have great potential to reduce seismic loss for regions close to an epicenter where damage is more likely to occur, and these regions could be within the blind zone of a regional EEW system.

Since the EEW system developed by the NCREE works quite well for past earthquakes, the Ministry of Education and the Ministry of Science and Technology in Taiwan have been facilitating the application of the EEW systems in all public elementary and junior high schools in Taiwan since 2014. The NCREE is also cooperating with local companies to popularize the EEW service with the general public. Hopefully, by combining emergency drills and automatic control devices, earthquake losses can be greatly reduced using the EEW techniques in the near future in Taiwan.

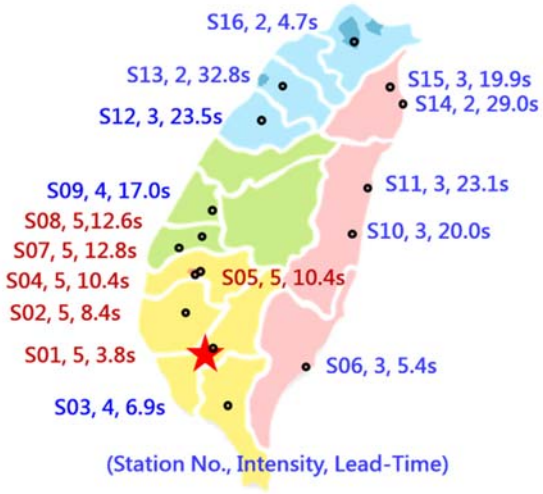


Fig. 8. Measured seismic intensities and lead times of sixteen on-site EEW stations shown on a map of Taiwan

Reconnaissance on Earthquake Damage of Low-Rise Buildings in the 0206 Meinong Earthquake

Pu-Wen Weng, Wen-Cheng Shen, Chao-Hsien Li, Assistant Researcher
Tsung-Chih Chiou, Associate Researcher, Lap-Loi Chung, Division Director, Shyh-Jiann Hwang, Deputy Director General

Damage to buildings caused by the Meinong earthquake was mainly concentrated in Tainan area. As soon as the earthquake occurred, staff at the National Center for Research on Earthquake Engineering immediately collected disaster information from the Internet and summarized preliminary information on the major locations of disastrous damage to buildings for reconnaissance teams to perform post-disaster work.

Our reconnaissance team for earthquake damage to buildings consisted of the following departments and agencies: 1. The Department of Architecture and the Department of Civil Engineering at National Cheng Kung University. 2. The Department of Construction at the Kaohsiung First University of Science and Technology. 3. The Department of Land Management and Development at the Chang Jung Christian University. 4. The Architecture and Building Research Institute at the Ministry of the Interior. 5. Structural technicians. 6. The National Center for Research on Earthquake Engineering. On February 6, the initial stage of the post-disaster work was performed. The main objective of this stage was to confirm the location of disasters, the mechanism of the damage, and to carry out a preliminary assessment of the disaster. The sections below report the progress and the results of the post-disaster survey on a few major disaster locations.

Dajhih Market in the Eastern District of Tainan City

Dajhih Market is located in Lane 103, Chang Dong Street, Eastern District, Tainan City. This building, a multi-span apartment, has four stories above ground level as well as one underground level. Due to the usage requirements of the market, it can be observed that, there are almost no partition walls on the first floor, and there is only brick wall in one corner. Therefore, a weak bottom story is formed. After the earthquake, the columns experienced destruction due to axial forces, and the weak story collapsed. Certain areas consisting of brick walls did not collapse (as shown in Figure 1). Fortunately, at the time of the earthquake, the market was not open for business and no one was trapped under the collapsed bottom story. Only one person at the residential level was injured.



Fig. 1. Dajhih Market Collapsed after the earthquake

Residential building in Lane 101, Taizi Road, Rende District, Tainan City

This building is located in Lane 101, Taizi Road, Rende District, Tainan City. There are three stories above ground level, and one story metal house that is constructed on the rooftop. The building was established in 1980; thus, the vertical elements have insufficient seismic capacities. In addition, the structure of the system was poorly configured, therefore torsion was experienced, and the weak story collapsed (Figure 2).



(a) Original building (Google Street View)



(b) Condition of the collapse
(Provided by Professor Yi-Hsuan Tu)

Fig. 2. Residential building in Taizi Road, Rende District

Residential building in Mingzhu Road, Yujing District, Tainan City

The earthquake had a greater impact on the Yujing District. This residential building is located on Mingzhu road, Yujing district, Tainan City. It is a common street building with three stories above ground level. It was established around 1989. The building did not suffer severe collapse, but residential units within the building were damaged. Obvious shear damage can be observed around the brick wall at the partitions (Figure 3)



(a) Shear damage on the brick wall, (b) X-shaped shear crack on the brick wall
Fig. 3. Residential building on Mingzhu road, Yujing district

Yujing Junior High School in Yujing District, Tainan City

Yuling Junior High School is located at 152 Dacheng Road, Yujing District, Tainan City. The school currently has five buildings, namely "Special Education Classroom", "Activities Center", "Diligence Building", "Benevolent Building", and "Simplest Building". The buildings that were damaged as a result of the earthquake were the "Special Education Classroom" and "Activity Centre".

The "Special Education Classroom" is a building constructed of reinforced concrete with three stories above ground level. The structure includes a single corridor and columns outside of the corridor. It was established around 1966. In 2010 during the 0304 Jiasian earthquake, a portion of this building experienced falling of tiles, and the partition walls in the classrooms had slight cracks. After this earthquake, the windowsill columns on the first level appeared to have diagonal shear cracks, and damage to the backside of building was especially severe. After research and assessment, it was determined that the columns were restrained by windowsill at the upper and lower ends, and therefore shear damage occurred (Figure 4). In addition, due to the shaking caused by the earthquake, the suspended ceilings (fabricated from light steel frames) had collapsed close to the edges on the second level and the third level of the building (Figure 4). During the post-disaster onsite survey, the school had already blocked and isolated the danger zones in order to maintain the safety of teachers and students.

The "Activities Center" is a building constructed of reinforced concrete with three stories above ground level. The structure includes a single corridor and columns outside of the corridor. It was established around 1975. The external building of the "Activities Center" was damaged by the earthquake. It was observed that tiles fell off the wall. The concrete blocks at the external frames of the windows crumbled, and the window glass was broken (Figure 5a). Inside the Activities Center near the uppermost section of the frame, it could be observed that at the interface between the bottom of the beam and the red bricks cracked significantly (Figure 5b). On both sides of the pipelines, the red bricks could not withstand the shaking from the earthquake and had fallen off (Figure 5c). In addition, in this building, numerous diagonal cracks were observed between the columns and the adjacent brick wing walls (Figure 5d).



(a) Shear damage on the brick wall, (b) X-shaped shear crack on the brick wall
Fig. 4. Earthquake damage in the Special Education Rooms in Yujing Junior High School



(a)External tiles fell off and windows were damaged, (b)Cracking at the interface between the bottom of the beam and the brick wall



(c) Around the pipelines, red bricks fell, (d) diagonal cracks between the column and the brick wing wall
Fig. 5. Earthquake damage to the Activities Centre in Yujing Junior High School

In addition to the damage in the abovementioned buildings, the school also suffered damage to various water tanks, as shown in Figure 6.



Fig. 6. Damage around various water tanks in Yujing Junior High School

Guiren Junior High School in Guiren District, Tainan City

Guiren Junior High School is located at No.2, Section 2, Houshili Wenhua Street, Guiren District, Tainan city. The school has a total of 10 buildings, including the "Knowledge Building", "Inspiration Building", "Success Building", "Xiang Jiang Building", "Yangming Building", "Gezhi Building", "Guanghua Building", "Activities Center", "Music Classroom", and "Folk Music Classroom".

The earthquake caused two buildings to suffer damage, the "Guanghua Building" and "Gezhi Building". The "Guanghua Building" is a building constructed of reinforced concrete with three stories above ground level. The structure includes a single corridor with no columns outside of the corridor. It was established around 1987 and had a seismic detailed assessment carried out in 2009. The assessment results showed that it had insufficient seismic capability (CDR = 0.706) and required retrofit. During the same year, the retrofit design was completed, however, funds to implement the retrofit have not yet been made available. The post-disaster survey indicated that, due to the earthquake, columns at the first level of the building experienced shear damage (Figure 7a).

The "Gezhi Building" is constructed of reinforced concrete with four stories above ground level. The structure includes a single corridor with no columns outside of the corridor. It was established around 1988 and a detailed assessment of this building was completed in 2014. The assessment results showed that it had insufficient seismic capability (CDR = 0.969) and required retrofit; however, funds to implement the retrofit have not yet been made available. The post-disaster survey indicated that, due to the earthquake, shear damage was observed in the walls. In addition, the expansion joints were damaged due collision with the next building (Figure 7b).



(a) Shear damage to columns in Guanghua Building, (b) Expansion joint damage in Gezhi Building

Fig. 7. Earthquake damage in Guiren Junior High School

In addition, four buildings in the school had completed projects on structural seismic retrofit, namely Yangming Building (wing wall retrofit), Knowledge Building (column jacketing retrofit), Inspiration Building (column jacketing, wing wall retrofit), and Folk Music Classroom (wing wall retrofit). During the earthquake, none of these buildings showed any structural damage. This confirmed that retrofitting structural could be beneficial to withstanding earthquakes. The completed retrofit buildings are shown in Figure 8.



(a) Yangming Building



(b) Knowledge Building



(c) Inspiration Building



(d) Folk Music Classroom

Fig. 8. Reinforced buildings in Guiren Junior High School

District Office in Nanhua District, Tainan City

The District Office in Nanhua District is located at 230 Nanhuali Nanhua District, Tainan city. The building is constructed of reinforced concrete with three stories above ground level (Figure 9a). The first level is utilized for office use for the district office. There were no internal partition walls, and there were only infilled brick walls at the rear of the building. The building did not

collapse during the earthquake, but a large number of building columns experienced shear damage. Some of the concrete cover of the column experienced severe spalling, and the steel bars inside the columns were exposed. The pipes inside the column can be seen (Figure 9b).



(a) Exterior of the district office



(b) Shear damage to the column. Pipes inside the column are visible

Fig. 9. Earthquake damage at the district office in Nanhua District

District Office of Guiren District, Tainan City

The District Office in Guiren District is located at No. 2, Section 2, Zhongshan Road, Guiren District, Tainan City. The building is constructed of reinforced concrete with three stories above ground level (Figure 10a). The first level is open space and used for office use for the district office. During the 921 earthquake, this building suffered damage. In 2011, seismic retrofit were implemented. At the front and the rear of the building, four shear wall segments were configured (Figure 10b). During this earthquake, no structural damage was observed. Therefore, it was confirmed that structural seismic retrofit could indeed improve the overall seismic capacity of the building.



(a) Exterior of the district office



(b) No structural damage was recorded on the RC walls

Fig. 10. Earthquake damage in district office in Guiren District

Reconnaissance on Earthquake Damage of Mid to High-rise Buildings

Yuan-Tao Weng, Fu-Pei Hsiao, Associate Researcher

Since the population is dense and the basement is not considered as floor area, deep excavation is very common for mid- to high-rise buildings. The basement is usually used for parking cars. In order to maximize the number of cars to be parked and to provide enough space for the mobility of the cars, the number of columns is minimized and the span between columns is maximized. Due to lack of redundancy, once one of the columns is damaged, the rest of columns will be damaged sequentially. Mid to high-rise buildings, of at least seven stories high and composed of several units, are often lined up in a row along the street. 16 mid to high-rise buildings in Tainan City, which were constructed before 1999, were investigated in the first-stage evaluation after the earthquake. The mid to high-rise building reconnaissance includes commercial/residential buildings and residential buildings. These mid to high-rise building damage modes can be summarized as follows: (1) presence of soft and weak first story, (2) lack of redundancy, and (3) lack of lateral reinforcement.

In urban and township areas, the most common building structure is the mixed commercial and residential building designed with a corridor to provide pedestrian walkway. Along the corridor, there are doors and windows for entrance and natural light, and no walls are continuous in the gravity direction. Damage was observed in this type of building. In addition to the provision of corridors, large openings for doors and windows are necessary at the street side of the buildings. Moreover, if the developers, builders, or owners provide open space for the public at the ground level, they are allowed to build more floor areas as a reward. On the other hand, the frames above the ground floor are in-filled with a brick masonry perimeter and partition walls. Thus, the bottom floor is comparatively soft and weak due to the presence of corridors, the open front, and open space. This is the case of soft first-story damage mode. The reconnaissance results of three representative mid to high-rise buildings during the earthquake are introduced as below.

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.

The Weiguan Jinlong Building, unfortunately, collapsed during this earthquake, leading to 115 deaths and 96 injuries. Figure 1 Survey results showed that the main column reinforcements were spliced in the same elevation. The reinforcements were detached from the splices while the hook of column transverse reinforcements exhibited a bending angle of only 90 degrees. Estimates from the structural layout diagram currently available (Figure 2)showed that only a single bend was provided on the shorter side, with low structural redundancy. The side next to 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 subject to axial compressive forces, while columns on the other side were subject to axial tensile forces. The columns may be damaged if their strengths were unable to withstand the seismic forces. At the same time, bar arrangement details 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, the splices may be loose, or the main column reinforcements may be spliced in the same elevation) which resulted in adequate strength and 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) Splices were located along the same plane

(b) 90 degrees hook of the column transverse reinforcement

Fig. 1. Photograph depicting the devastation of the Weiguan Jinlong Building in Yongkang District

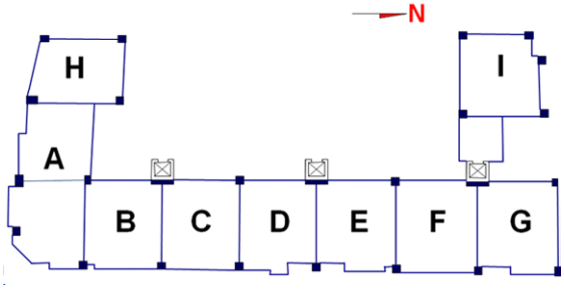


Fig. 2. Structural layout of Weiguan Jinlong Building at Yongkang District (provided by Dr. Jui-liang Lin)

King's Town Bank, Sin-Hua Branch

King's Town Bank is located at No. 586 Zhongshan Road, Sin-Hua District, Tainan. The building has 11 above ground floors and 1 basement floor. This building was constructed at 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 subject 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 3).



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



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

Fig. 3. Collapse of the King's Town Bank Building in Sin-Hua District

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 at about 2000. The 1st and 2nd floors of this building was 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 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 4). 1 person was injured in this building.



(a) Collapse of the building



(b) Damaged connectors at the columns and beams

Fig. 4. Collapse of Xingfu Building at Gueiren District (provided by Dr. Yu-lin Chung)

Soil Liquefaction, Landslide, and Revetment Failure

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Kuo-Lung Wang, National Chi Nan University, Chi-Chin Tsai, National Chung Hsing University
Chia-Han Chen, Assistant Researcher

Introduction

In the Tainan area of Southern Taiwan, the geotechnical damage caused by the Meinong earthquake included liquefaction, settlement and tipping of buildings caused by soil liquefaction, waterfront landslides, and failure of embankments and revetments along the Zengwun River. This damage was observed during field investigations conducted by a survey team from the National Center for Earthquake Engineering (NCREE). This paper summarizes the geotechnical damage features observed in two field investigations by a NCREE survey team, focusing on liquefaction, slope and levee failure, and dam performance. Figure 1 shows the location of featured instances of geotechnical damage, including liquefaction that led to different levels of structural damage in the Xinshi (L1) and Annan (L2) districts, landslides in the Nanbao golf course (S1), and failure of the embankments along the Zengwun River at the Rihsin embankment (E1, E2) and at the Jianshan revetment (E3).

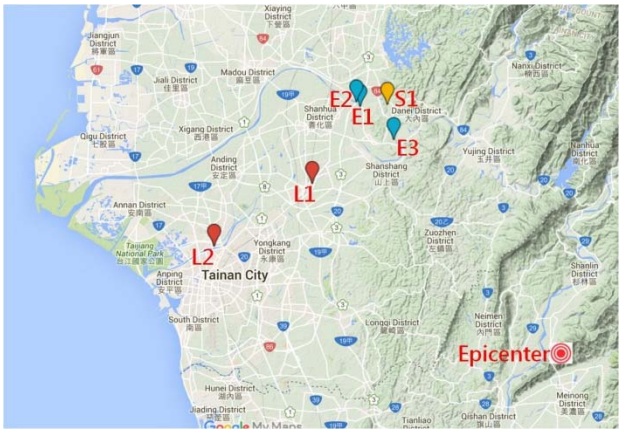


Fig. 1. Locations of geotechnical damage in Tainan area

Settlement and Tipping of Buildings Caused by Soil Liquefaction in Tainan

The following summarizes the outcomes of the post-earthquake geotechnical disaster investigation conducted by the NCREE with regard to the sinking and tipping of buildings caused by soil liquefaction.

Areas around Alley 10, Lane 50, Sanmin Street, Xinshi District, Tainan City (L1)

Soil liquefaction caused many houses in the area around Lane 50, Lane 50 Alley 10, and Lane 10 of Sanmin Street (as shown in Figure 2) to sink and tip (Figure 3A). On-site measurements showed that sand blasting reached as high as 150 cm (Figure 3B). Differential settlement due to weight differentials between garages and buildings was about 47 cm compared to the street level (Figure 3C). Sand boiling was also observed from drainage sewer manhole covers, utility poles, fire lanes, and drains around the buildings. In this area, damage was observed for ground-level garages and fences as well as sinking and slight tipping of the main buildings. No other visible structural damage was seen.



Fig. 2. Major damage area around Aly. 10, Ln. 50, Sanmin St., Xinshi Dist.



(a) Sinking and tipping of buildings



(b) Sand blasting reached as high as 150 cm
(c) Ground level floors sank about 47 cm

Fig. 3. Building tipping and sinking due to soil liquefaction at Alley 10, Lane 50, Sanmin Street, Sinshih District, Tainan City

After interviewing local residents and reviewing an old map of Taiwan provided by Academia Sinica (gissrv5.sinica.edu.tw/GoogleApp/JM20K1904_1.php), it was found that this area was once a pond that was later reclaimed by landfill in 1898~1904. Hence, severe liquefaction was observed in this area but not in surrounding areas.

Areas around Xiding Village, Annan District, Tainan City (L2)

Xiding Village, the most severely affected liquefaction area in An-Nan district, was located to the north of Old Tainan City and sandwiched between the south of Chianan Irrigation, the west of Section 2, Beian Rd., and the north of the Yanshuei 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 eruption from drains, manhole covers, and the bottom of utility poles.

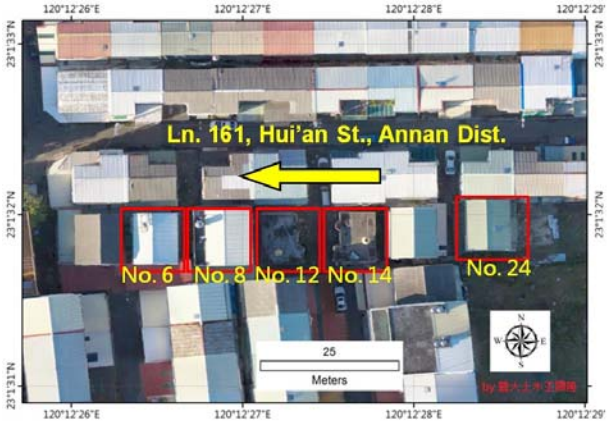


Fig. 4. Annan liquefaction area along Ln. 161, Hui'an St.



(a) Building at No. 24, Lane 161, Hui'an Street
(b) Building at No. 8, Lane 161, Hui'an Street
(c) Measuring the tipping angle in front of the house

Fig. 5. Building tipping and sinking due to soil liquefaction at Lane 161, Hui'an Street, Annan District

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 the 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 to the 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.

Landslide

Nanbao golf course (S1 in Fig. 1) is located in the Danei district, 30 km from the earthquake's epicenter. The elevation of the area impacted by landslides is approximately higher in the east and gradually decreases to the west. The average slope of the landslide area is about 5~8 degrees. The Liushuang river is adjacent to the western part and there is a pond to the northeast. An orthophoto of the landslide area taken using an unmanned aerial system (UAS) is shown in Figure 6. The cracks are mapped on the orthophoto and they are oriented parallel to the riverbank. The width of the crack area is about 20 m and the widest crack is about 6.5 m. The elevation difference is approximately 170 cm, as shown in Figure 7A. An overview of a crack and a broken pipe are shown in Figure 7B, which was taken from the ruptured road to the northeast.

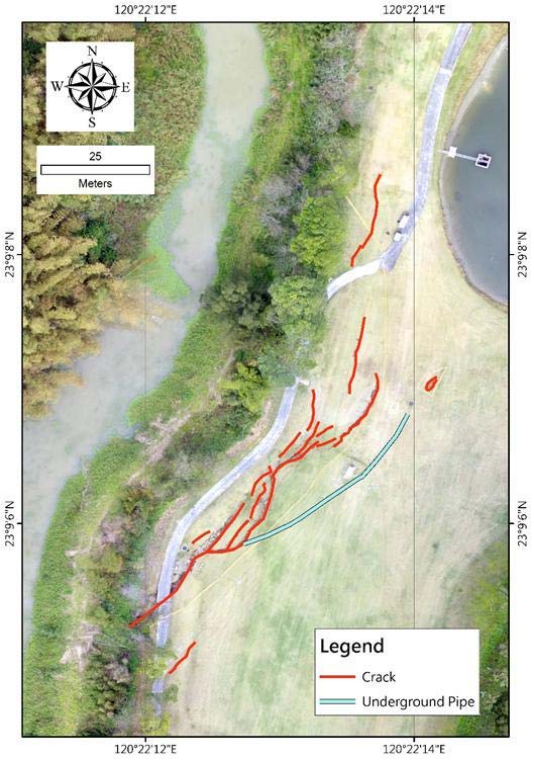


Fig. 6. Orthophoto and cracks of landslide at Nanbao golf course



(a) Maximum elevation difference is larger than 170 cm



(b) The crack view from ruptured road to northeast

Fig. 7. Landslide and elevation difference of Nanbao golf course

Embankment and Revetment Failure

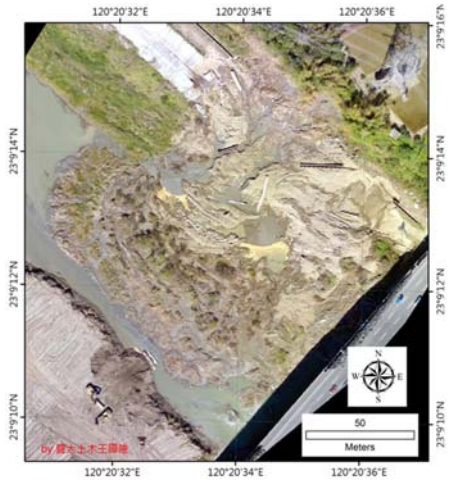
Three embankment failures and one revetment failure occurred along the right bank of the Zengwun River during the Meinong earthquake. Three flow failures of the Rihsin embankment occurred at the junction of Highway No. 3 and the Zengwun River. Subsidence and side displacement occurred at the Jianshan revetment.

Rihsin embankment (E1 and E2 in Fig. 1)

Two large failures A and B occurred at Rihsin embankment E1, as shown in Figure 8A. The dimensions of A block are about 150 m by 75 m and the dimensions of B block are about 75 m by 75 m. Another embankment failure, E2, was located on the other side of the Zengwun River bridge. The dimensions of E2 block are about 100 m by 125 m, as shown in Figure 8B.



(a) Failure block A and B of Rihsin embankment



(b) Failure block E2 of Rihsin embankment

Jianshan revetment (E3 in Fig. 1)

The Jianshan revetment is located at the right bank of the Zengwun River near the Er-Si bridge. Concrete slope cracks and torsion, and subsidence of the revetment road are found, as shown the red block of Figure 9. The length of failure is more than 100 m. Maximum subsidence of the revetment is more than 50 cm as determined by field investigation and UAS measurement. The maximum crack size is about 70 cm located at the vegetation area. Longitudinal cracks are also found in the concrete revetment walls. Moreover, liquefaction and sand blasting holes are found on the ground surface of farmland within the dike as shown in Figure 10.



Fig. 9. Cracks and failure of Jianshan revetment



Fig. 10. Sand boiling hole in the field near the Jianshan revetment

Damage to Nonstructural Components

Juin-Fu Chai, Shiang-Jung Wang, Research Fellow
Fan-Ru Lin, Wang-Chuen Lin, Assistant Researcher
George C. Yao, Professor, Wei-Chung Chang, NCKU

A survey of damage to nonstructural components (NSC) was conducted on two factories (one five-story SRC building and one six-story SC building) and one residential building (a thirteen-story RC building) located in an area where the PGA was between 80 and 250 gal (seismic intensity V, according to the Central Weather Bureau, Taiwan) during Meinong earthquake. The structures of these buildings retained structural integrity. Damaged NSCs can be divided into three categories:

1. MEP (mechanical, electrical, and plumbing services): Most damaged MEP components are located on the top and roof levels. The potential causes of observed damage to NSCs are insufficient anchorage strength and the vulnerable structural systems of the NSCs. For example, two freestanding canisters of a gaseous fire suppression system were displaced during the earthquake and were only supported on one side and suspended on the other side (Fig. 1). Spring isolators of a 4.2-ton chiller were broken by the excessive overturning moment resulting from the dynamic amplification effect of the flexible structural characteristics of the spring-isolated system (Fig. 2). Other damaged NSCs include a compressor, a tower, the chilled water piping of HVAC systems, connecting piping of the RO system, UPS panels on the top floor, and elevator systems.
2. Architectural components: damaged architectural components in surveyed buildings include suspension ceiling systems, interior granite veneers in elevator halls, nonstructural RC walls on the first floor, and a railing on the roof level. As shown in Fig. 3, the cracked nonstructural wall is the main damaged part of the thirteen-story RC residential building.
3. Contents and furniture: In this earthquake, broken and/or displaced instruments and equipment in the factories interrupted operations and caused economic losses. Displaced sensitive computer servers on the top floor of the six-story SC building caused network interruption during the strong motion as a result of a broken foot. Due to inadequate seismic design, most pieces of equipment with seismic restraints in the clean room were still displaced on the top floor of the five-story SRC building (Fig. 4).



Fig.1. The suspended side of a displaced freestanding canister of a gaseous fire suppression system on the top floor



Fig. 2. Broken spring isolators of a heavy chiller on the top floor



Fig. 3. A damaged nonstructural wall on the first floor of a 13-story RC building

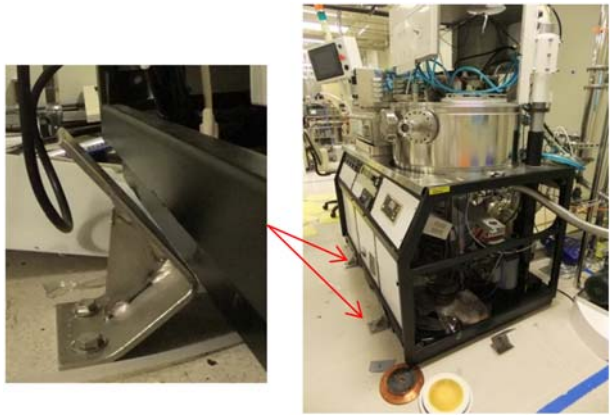


Fig. 4. Displaced instruments and related deformed stoppers in a clean room on the top floor

In Tainan City, there are currently four seismically isolated buildings, of which one is a national laboratory and the other three are residences (one is still under construction). The distances from these four buildings to the epicenter of the 0206 Meinong earthquake are presented in Fig. 5. In addition, a raised floor system in a national laboratory and high-precision equipment in a high-tech factory are designed with seismic isolation technology. During the quake, as expected, these isolated buildings exhibited excellent performance, thus

effectively protecting the housed human life and property from injury and damage. Furthermore, the isolated equipment remained functional during and after the quake, thus significantly reducing production losses and downtime cost in the high-tech industry. However, as shown in Fig. 6, some slight damage in expansion plates, piping, cable trays, and decorations were observed, owing to insufficient buffer space between the isolated and non-isolated structures (or components), which should be carefully designed and reserved to accommodate isolation displacement. The majority of cases were caused by users' inappropriate obstructions for their special purposes. Although these inappropriate obstructions did not affect the overall seismic isolation performance, repairs made after quakes are still inconvenient to users. Learning from these lessons, in the future, we need to pay more attention to these details in standard maintenance and inspection.

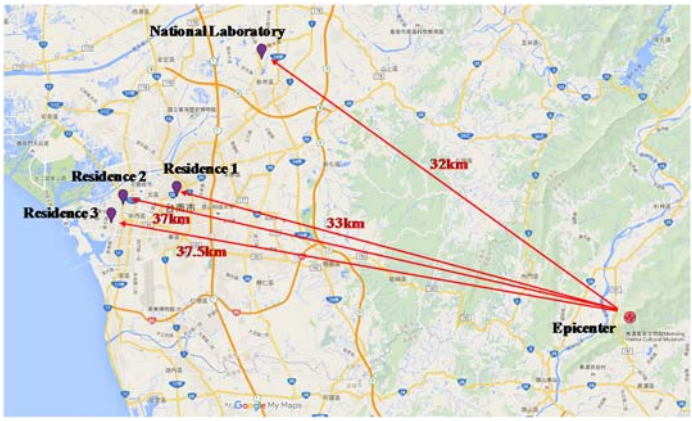
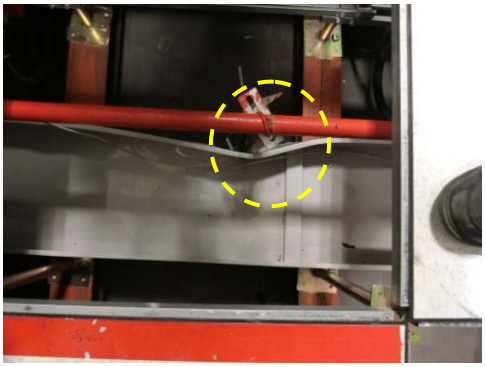


Fig. 5. Epicentral distances of the four seismically isolated buildings in Tainan City



(a) expansion plate



(b) cable tray



(c) decoration

Fig. 6. Slight damage of non-structural components

Performance of Water Systems

Gee-Yu Liu, Associate Researcher

The Meinong earthquake caused substantial damage to water pipelines in Tainan, especially in its southern area. The ϕ2,000-mm transmission pipeline conveying water from the Nanhua Water Treatment Plant was damaged at three sites, denoted as 1, 2, and 3 in Fig. 1. It is the largest and most critical pipeline supplying water to the downtown area. These damages caused widespread water outage lasting for quite some time.

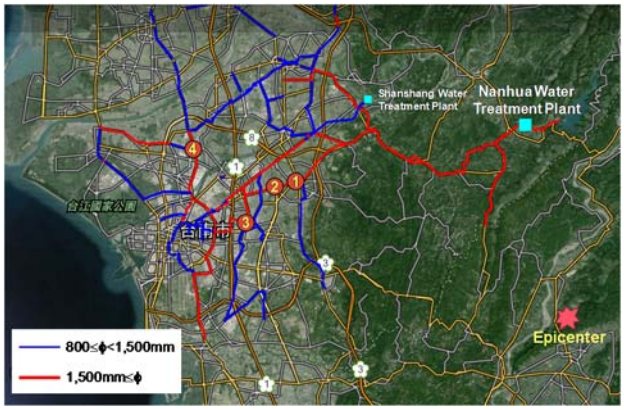


Fig.1. Water transmission network, damage sites, and the environment of southern Tainan

The damage at Site 1 occurred in a 1,205-meter pipeline consisting of steel double-skinned pipe segments filled with cement. They were installed by pipe jacking method, segment by segment at a depth of 8 m. Along the pipeline, annular welds broke twice at the collars where two segments from opposite sides met. Deep excavations (Fig. 2) and repair and enhancement of the pipeline were applied.



Fig.2. Deep excavations to reach the damaged steel pipe segments (Site 1)

Site 2 is located at the west end of Kei-Yun Bridge on Provincial Highway 20, where pipe slip-out occurred at a special joint between a concrete pipeline and a welded steel pipeline from a nearby water pipe bridge. It was quickly repaired without any difficulty.

Site 3 is located just in front of Weiguan Jinlong building. A pre-stressed concrete pipeline (PSCP) around one hundred meters long was severely damaged by the building collapse. In addition, an adjacent steel pipe lying at a right angle to the concrete pipe was torn apart for 30 cm evenly along the annular weld. This is presumed to be a result of ground displacement during the collapse. The repair work cannot be commenced until the completion of search and rescue. The damaged PSCP was replaced with ductile iron pipes (DIP), as shown in Fig. 3.



Fig.3 DIP replacement for the damaged PSCP in front of the Weiguan Jinlong building (Site 3)

Another damage site in the transmission pipelines, denoted as 4 in Fig. 1, was located in the north of the downtown area. Pipe leakages were observed there along a ϕ1,500-mm pipeline several hundred meters long. It consists of steel pipe segments connected by flange.

For smaller pipelines, thousands of cases of damages have been reported, mostly in customer pipes. Notably, clusters of pipe damages were identified in An-nan, Guan-miao, and Yuh-ching. Localized soil liquefaction or ground deformation may be responsible for these damages.

All water supply facilities survived the earthquake, except the Shanshang Water Treatment Plant, a small plant that was slightly damaged. A partition wall of its sedimentation basin cracked and tiled. Three out of the five 3-ton chemical storage tanks were damaged in the inlet and outlet pipes, one of which broke at the bottom and lost all its contents.



Fig.4. Damages to the Shanshang Water Treatment Plant

Exploration of Meinong Earthquake using UVA Aerial Photography and 3D Laser Scanning

Ren-Zuo Wang, Associate Researcher

The National Center for Research on Earthquake Engineering (NCREE) immediately discussed the matter of aerial photography and 3D laser scanning to survey the site and then contacted the team (Dr. Ren-Zuo Wang) for aerial photography and 3D laser scanning just six hours after the 0206 Meinong earthquake occurred, and finished this work on February 19, 2016. The content of aerial photography includes the Weiguan Jinlong building, the Changan Street Dali Market, the Xinyi North Street Xingfu Building, Xinhua Jingcheng Bank, Wind Temple, and 86 Highway Bridge. The content of the 3D laser scanning includes the Weiguan Jinlong building, 86 highway Bridge, and the professional classroom and hall of Yujing Junior High School. The emphasis of this earthquake site survey includes (1) a plan of aerial photography and 3D laser scanning sites and a GPS test, (2) setting up reference positions for aerial photography and 3D laser scanning, (3) asking relevant engineering and relief units for assistance, (4) planning the route of aerial photography and 3D laser scanning, (5) the position of a temporary workspace for scanning. The purpose of planning the aerial photography and 3D laser scanning sites and the GPS test is to understand conditions of receiving GPS signals around the bridges, the relationship with picture quality, and the convenience of data arrangement with different aerial photography angles. The reference positions for aerial photography and 3D laser scanning are set in order to accurately measure the sizes, while the field team also measures the sizes using theodolites. The planners also tried to set common reference positions for aerial photography and 3D laser scanning so that the data of aerial photography and 3D laser scanning may be combined.

Asking the relevant engineering and relief units for assistance provides knowledge of the damage in the disaster area, arranges necessary equipment, and assists with earthquake data collection. For example, the support of the 86 Highway Bridge was badly damaged in the earthquake, so an aerial platform vehicle was needed to scan in a handheld manner. During the scanning of the bridge support, when the staff on the aerial platform vehicle were very close to the support, the nearby part of the support can be scanned in detail. The method for scanning the bridge bottom was to use a fixed point at a large scale. The whole bridge point-cloud model was constructed by combining handheld scanning and large-scale scanning data. Planning the route of aerial photography and 3D laser scanning involved surveying the area around the damaged bridge, and different degrees of point-cloud scanning were required for the damaged bridge columns, box girders, abutments, and supports.

Some staff arrived in the bridge area a day before formal scanning work commenced in order to plan the route, including how to set reference points, the positions of reference points, scanning directions, and how to set up scanning equipment. Setting up a temporary workspace for scanning was necessary because aerial photography and 3D laser scanning require electricity, and so staff can check the 3D laser scanning results at any time, to improve data reliability and validity. It also avoids a situation in which the bridge is removed too soon, so that follow-up supplemental photography and scanning cannot be performed. The structures that took the most time to collect data for were the Weiguan Jinlong building and 86 Highway Bridge. The Weiguan Jinlong building was the most badly damaged building and it had the largest number of casualties. The 86 Highway Bridge has great influence on traffic and is the most difficult structure to reconstruct.

The most difficult part of the survey of the Weiguan Jinlong building is to find a good height for photography and scanning so that high-quality pictures and complete scanning data can be made. The staff asked relief personnel and citizens for assistance in the field, choosing an area of almost positive triangle surrounding the Weiguan Jinlong building from above, and choosing the top floors of three buildings as a workspace for data collection, with the aim that there is no impact on disaster relief. Pictures of the aerial photography and scanning are shown in Figs. 1 and 2.



Fig 1. Aerial photograph of the Weiguan Jinlong building



Fig 2. 3D laser scanning image of the Weiguan Jinlong building

One benefit of the aerial photography is that, besides shooting an image of the bridge deck from high altitude, an image of the bridge bottom is shot from low altitude as well. The area of the high-altitude aerial photography includes the whole bridge (Fig. 3). The focus of high-altitude aerial photography is the bridge deck and the expansion joints, which are the most badly damaged parts (Fig. 4). The emphasis of the low-altitude aerial photography is the bridge column and support.



Fig 3. Aerial photograph of 86 Highway Bridge

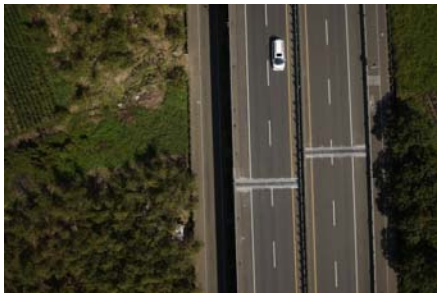


Fig 4. Aerial photograph of the most badly damaged position of the expansion joints on the 86 Highway Bridge deck

After the field survey, the staff decided to scan the most badly damaged bridge supports (Nos. P5 to P10), which was also the main scanning range of the entire bridge working area. The bridge columns, supports, and expansion joints were the focus of scanning in this survey (Fig. 5).



Fig 5. Point-cloud 3D laser scanning data picture of 86 Highway Bridge

The aerial pictures of the Changan Street Dali Market, Xinyi North Street Xingfu Building, Xinhua Jingcheng Bank, and Wind Temple are shown in Figs. 6 to 10. The 3D scanning results of the professional classroom and hall of Yujing Junior High School are shown in Fig. 11.



Fig 6. Aerial photograph of Yujing junior high school



Fig. 7 Aerial photograph of the Changan Street Dali Market



Fig. 8. Aerial photograph of the Xinyi North Street Xingfu Building



Fig. 9. Aerial photograph of Xinhua Jingcheng Bank



Fig. 10. Aerial photograph of Wind Temple



Fig. 11. 3D laser scanning picture of hall of Yujing junior high school

This is the first time that the NCREE has used the latest technology in data collection in the exploration of the Meinong earthquake. It helps to accurately record losses and structural damage to buildings and structures after an earthquake, which is very useful for numerical simulation, analysis, and verification in the future. Comparing the results of numerical simulation with real data of damage can provide references for formulation and modification of design codes for earthquake resistance in the future.

The 2nd Workshop to Predict the Cyclic Test of 1/13-Scale Model of RC Nuclear Containment Vessel

Yu-Chih Chen, Assistant Researcher

Nuclear reactor containment vessel is the main civil infrastructure for protecting the public and preventing accidental release of fission products. Investigations of its structural strength are usually dominated by non-seismic accidents, such as extremely high thermal and pressure stresses due to core damage, or by threats of bombing by hostile countries or terrorists. Most US nuclear power plants are located on the East Coast or in the Midwest, which is a less seismically active area. This is different from Japan, which lies along the Pacific Ring of Fire, where earthquake activities occur frequently. Furthermore, many nuclear power plants are built in Japan to meet the high electricity requirements of industrial development. Hence, seismic risk is a prime concern for Japan as well as Taiwan. Unfortunately, the magnitude M_w-9.0 2011 earthquake off the Pacific coast of Tōhoku that occurred on Friday, March 11, 2011 seriously damaged the three reactor cores and containment structures in the Fukushima Daiichi Nuclear Power Plant. Many electrical generators were taken down, and three nuclear reactor units suffered explosions as a result of hydrogen gas that had built up within the secondary containment buildings after the failure of the cooling system resulting from the loss of electrical power. Thus, improving the safety of nuclear energy infrastructures has become a hot topic for public discussion. As mentioned above, containment plays an important role in ensuring the safety of nuclear plants. For this purpose, two research groups of the National Center for Research on Earthquake Engineering (NCREE) and the University of Houston (UH) aim to understand the behavior of a cylindrical shell wall as a containment vessel in order to verify the numerical model of reinforced concrete (RC) through experimental testing, that is, a 1/13th-scale model of an RC nuclear containment vessel. Before the test, the First Workshop to Predict the Cyclic Test of a 1/13th-Scale Model of the RC Nuclear Containment Vessel was organized and held on March 5, 2015.

From the test results, we found some interest data and it is necessary to carry out a second test of containment in 2016 in order to acquire more useful details. To propagate knowledge and communicate with other advanced researchers in the field of seismic technology, the second workshop (Fig. 1) was held before the experimental testing. We invited Professors Thomas T. C. Hsu from the University of Houston, Alice Hu from City University of Hong Kong, and Beatrice Belletti from the University of Parma to give presentations in related fields, and also invited the Vice President of National Applied Research Laboratories, Jough-Tai Wang, to thank Professor Hsu for his contribution in offering the NCREE a steel L-frame, which is indispensable to the second test (Fig.2). A tour (Fig.3) to introduce the experimental setup and the specimen was given at the end of the workshop.



Fig.1. The 2nd Workshop to Predict the Cyclic Test of a 1/13th-Scale Model of an RC Nuclear Containment Vessel

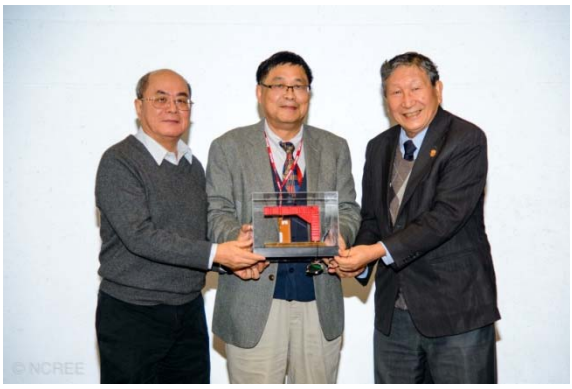


Fig.2. The donation ceremony for Professor Thomas T.C. Hsu of UH (right), with Vice-President Jough-Tai Wang (center) of NARLabs, and Director-General Kuo-Chun Chang (left) of NCREE



Fig.3. A tour to introduce the experimental setup and specimen

A Workshop for Design Guidelines of High-Strength RC (New RC) Structural Systems in Taiwan

Ker-Chun Lin, Research Fellow

As most of the population of Taiwan is concentrated in metropolitan areas, the construction of high-rise buildings is one of the most effective methods of reducing demand for building space in urban areas, and of creating more comfortable living spaces for people. In Japan, design and construction technology for high-rise reinforced-concrete (RC) buildings with high-strength materials have successfully developed. Many high-rise RC buildings have been constructed, including a 59-story residential building constructed in 2009. The Japanese experience is therefore worth learning in Taiwan's construction industry.

From 2010, the National Center for Research on Earthquake Engineering (NCREE) launched an integrated research program, called "Taiwan New RC Project", to bring together related construction companies, industrial societies, and academic researchers, called the "Taiwan New RC Group", for research and development on high-strength RC materials, members, and structural systems. For goal strength of materials at this stage of the Taiwan New RC Project, SD 685 steel for main bars and SD 785 steel for transverse bars, and the concrete design strength of 70 to 100 MPa are set. By the end of 2015, the Taiwan New RC Project had accumulated rich research results and was devoted to publishing a first version of the Design Guidelines for High-Strength Reinforced-Concrete (New RC) Structural Systems for practical high-strength RC building design in Taiwan.

This workshop was held in the R101 Conference Room of the NCREE on December 11, 2015, and attempted to demonstrate the research results and findings of the Taiwan New RC Group and to present the first version of the Design Guidelines for High-Strength Reinforced-Concrete Structural Systems to construction societies in Taiwan. The workshop not only presented high-strength materials such as steel bars and concrete, and splice and end anchorage devices for bars, but also introduced design methodologies for main structural members, including columns, beams, shear walls, and coupling beams. In this meeting, many enthusiastic and positive responses were obtained from Taiwan's construction societies.



Symposium on Seismic Design, Testing and Applications of Buckling-restrained Braced Reinforced Concrete Frames

An-Chien Wu, Assistant Researcher

Buckling-restrained braces (BRBs) can be conveniently fabricated using common construction materials and techniques. Buckling-restrained braced frames (BRBFs) employing BRBs offer desirable seismic-resistant lateral strength, stiffness, and ductility. The innovative connection of the welded en-slot BRB developed by NCREE improves the stability and fatigue life of the device. Patents for this invention have been approved in Taiwan, China, Canada, Japan, Korea, Italy, and the US. The technology of the invention has been transferred to seven steel fabricators in Taiwan and one in New Zealand. More than 3,500 pieces of the device have been fabricated and installed in more than forty buildings over past four years.

A symposium was held on November 13, 2015, introducing our most recent BRB research and applications for new construction and retrofitting of buildings. More than 100 engineers attended this symposium. In this symposium, a novel method of retrofitting reinforced concrete (RC) frames with BRBs using high-strength mortar blocks constructed at the four corners of the RC frame was proposed. For the construction of new RC buildings, an I-shaped steel embedment was proposed as an interface for BRBs and RC members. Based on hybrid and cyclic tests of a two-story full-scale RC frame with BRBs, seismic design and analysis methods for using the proposed steel embedment in RC frames were also presented. Several Taiwanese engineers were invited to share their experiences in the implementation of BRBs in RC structures.



Symposium on November 13, 2015

Workshop on Activities of Volcanic Eruptions, Volcanic Earthquakes, Mud-cored Anticlines, Mud Diapirs, and Mud Volcanoes in the Taiwan Area

Kuan-Yu Chen, Assistant Researcher

The NCREE held a full day workshop, entitled "The activities of volcanic eruptions, volcanic earthquakes, mud-cored anticlines, mud diapirs, and mud volcanoes in the Taiwan area", on January 27, 2016, at R103 of NCREE. Attendance, which ran to 100 people, not only from NCREE but also from AEC, INER, TPC, CWB, CGS, SINICA, ITRI, Sinotech Ltd Inc., NTU, NCU, NCKU, and PCCU were registered as participants for this workshop.

This workshop explored two topics, the activity of volcanoes and of mud diapirs. We invited two experts on volcanic activity: Professor Cheng-Hong Chen, Department of Geosciences, National Taiwan University, presenting volcanic activity in Taiwan: past, present, and future, and Professor Cheng-Horng Lin, Academia Sinica, presenting seismic signals recorded in volcano area, Northern Taiwan. We also had two experts on mud diapirs: Professor Andrew Tien-Shun Lin, Department of Earth Sciences National Central University, presenting an introduction to mud-cored anticlines, mud diapirs, and mud volcanoes in SW Taiwan and offshore areas; and Doctor Song-Chun Chen, Central Geological Survey, presenting distribution and characteristics of mud diapirs and faults in the vicinity of west Hengchun hill in south Taiwan.

Taiwan, located on the earthquake-prone Pacific Rim, is an orogeny on a convergent boundary between the Eurasia Plate and the Philippine Sea Plate, where it experiences high earthquake and volcanic activity. Consequently, many earthquakes caused by active faults occur in Taiwan. One of the major geological hazards is the shaking caused by earthquakes and the damage that can result, for example, the Chi-Chi earthquake and the Tsaoling landslide that it triggered. Most people only pay attention to earthquake hazards caused by faulting and ignore other hazards from geological activities such as volcanic eruption, volcanic earthquakes, lahars, mud diapirs, and mud volcanoes. They are capable of causing significant damage and destruction to our environment, but they do not cause large ground motions. The purpose of this workshop is to raise awareness of non-ground shaking geological hazards among scholars and experts.



Professor Cheng-Hong Chen talking about volcanoes

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