Learning from Earthquakes
The M_L 6.7 (M_W 7.1) Taiwan Earthquake of December 26, 2006

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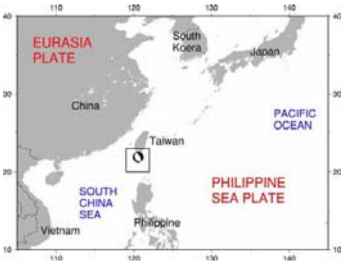
This report presents the observations of several reconnaissance teams that assessed the earthquake damage. The information mainly came from NCREE, NCDR, Pingtung University of Science and Technology and National Cheng-Kung University.

Overview

On December 26, 2006 at 8:26 pm local time, a M_L 6.7 (M_W 7.1) earthquake rocked southern coast of Taiwan, about 22.8 km southwest from Hengchun (90 km from Kaohsiung). About 8 minutes later (8:34 pm local time), the first aftershock with M_L 6.4 (M_W 6.9) hit the region again followed by the second aftershock with M_L 5.2 at 8:40 pm. Most of the buildings survived without any damages during these earthquakes. However, a few street-front commercial /residential buildings, hotels and elementary schools have experienced moderate to severe damages. Especially a 4-story furniture store with possible soft first story was collapsed. Several fire outbreaks were reported right after the earthquakes. There were totally 2 casualties, 45 people injured, 3 apartment buildings collapsed as well as 134 schools damaged as reported by Pingtung County government. Besides, the earthquakes also damaged several undersea fiber-optic cables used to route internet and telephone services, disrupted the businesses in Taiwan, Hong Kong, Japan, China, South Korea, Philippines, Malaysia, Singapore, and Thailand. The reconnaissance team formed by NCREE and NCDR visited the sites of damaged buildings with the following observation.

Tectonics/Strong Ground Motion

Taiwan island is in the interaction zone of the Eurasia and Philippine Sea plates. The 3 tectonic units of southern Taiwan as identified are, the Eurasia (South China Sea), the Taiwan Island (Kenting penin-



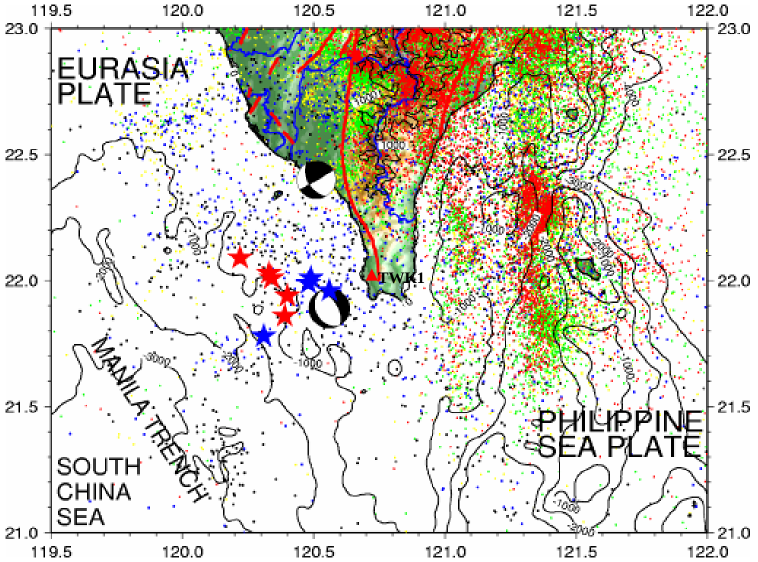


Fig. 1 The earthquake focal mechanisms of the main shock and its biggest aftershock are shown. The other aftershocks are shown as stars. The red stars are shallower than 30 km, the blue stars are those deeper than 30 km. The small dots indicate the seismicity for the past 16 years. The red, green, yellow dots are shallower than 10, 20, 30 km respectively. The blue and black dots are deeper than 30 and 50 km.

sula) and its surrounding accretion wedges, and the Philippine Sea plate. The Philippine Sea plate is moving north-westward and is forcing the Eurasia plate to submerge eastward. The loosely marine sediments have been pushed westward to form the accretion wedges and finally emerges as the Taiwan Island. The Manila trench is the boundary between these two oblique colliding plates.

The main shock and its biggest aftershock 8 minutes later represent two major type focal mechanisms (Fig.1). The main shock is a normal faulting event which means the upper part of subducting Eurasia plate is undergoing the tensional force caused by its overburden of thickening accretion wedges. Therefore the strike of the rupture plane is parallel to the Manila Trench. The biggest aftershock is a strike-slip faulting event which means the accretion wedges undergo the north-western compression force being pushed by the Philippine Sea plate. The rest of the aftershocks can be grouped as two parts according to their focal depths. The deeper aftershocks (> 30 km) are roughly perpendicular to the Manila Trench and become deeper north-eastward. The shallow aftershocks (< 25 km) are parallel to the trench. The preliminary results suggest the main shock released the tensional strains in the subducting Eurasia plate and immediately trigger to release the accumulated com-

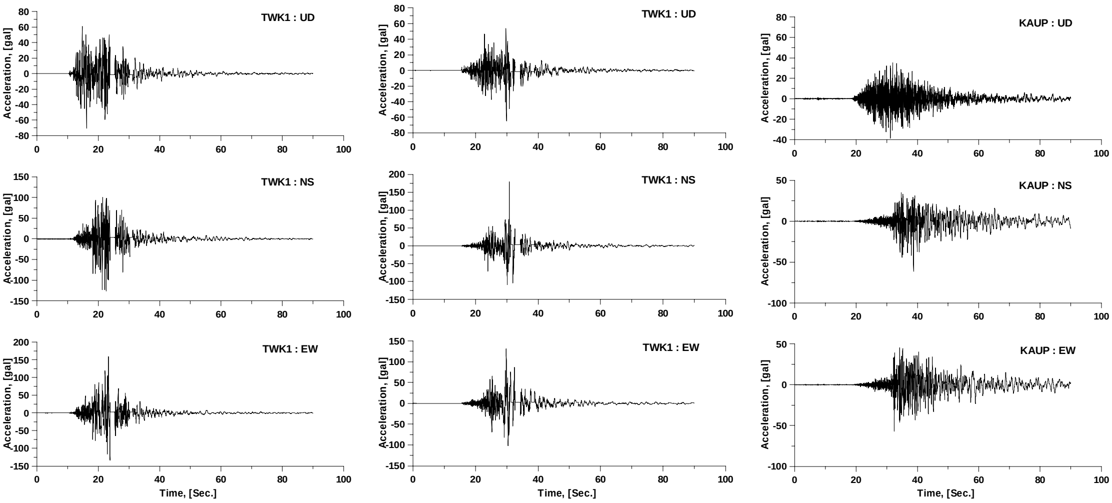


Fig. 2 The ground accelerograms recorded at RTD stations TWK1, KAU and KAUP in M_L 6.7 main shock

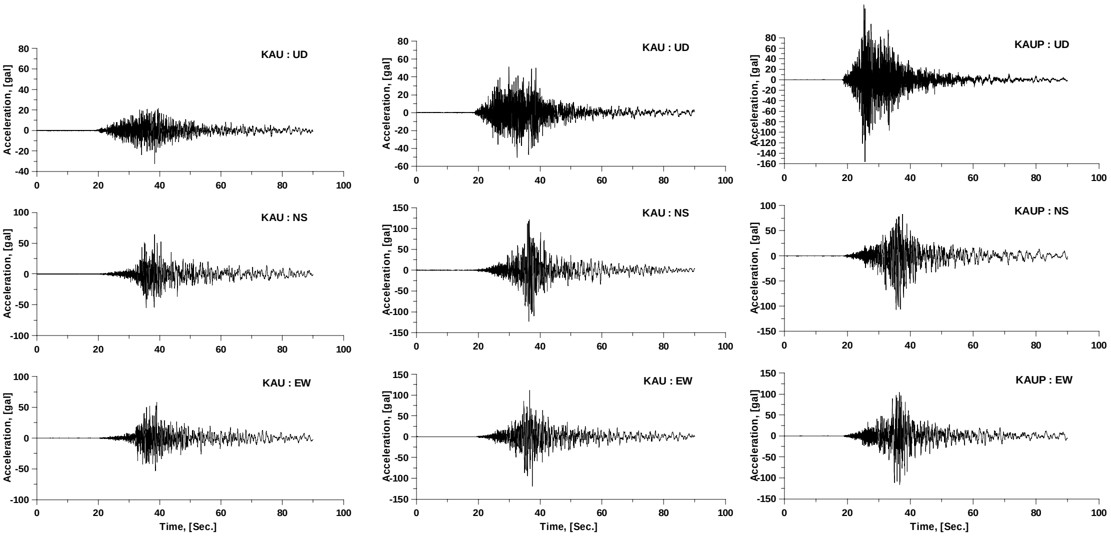


Fig. 3 The ground accelerograms recorded at RTD stations TWK1, KAU and KAUP in M_L 6.4 aftershock

Table 1 PGA records of main shock (M_L6.7)

Station ID	Epicentral Dist.(km)	PGA (cm/sec^2)	Sa(T=0.3) (cm/sec^2)	Sa(T=1.0) (cm/sec^2)
TWK1	26.206	159.6	316.1	244.8
KAU	78.805	64.5	171.4	60.3
KAUP	77.794	61.3	154.9	67.6
SSD	94.727	73.5	117.2	24.3
SPT	86.962	64.9	176.8	91.5
WCH	242.819	60.7	104.3	12.9
SCK	147.193	61.5	129.0	26.0
SGL	92.458	53.3	135.4	95.8
SCL	146.878	47.9	104.4	24.3
SCZ	53.831	48.9	88.1	28.6
TAW	61.989	47.4	132.3	67.9
CHN3	132.453	46.9	102.1	26.2
TAI2	126.441	40.0	80.9	20.1
TCUP	261.677	32.7	90.8	30.6
PNG	211.931	35.9	46.6	7.2
TWK1	26.206	159.6	316.1	244.8
KAU	78.805	64.5	171.4	60.3

Table 2 PGA records of aftershock (M_L6.4)

Station ID	Epicentral Dist.(km)	PGA (cm/sec^2)	Sa(T=0.3) (cm/sec^2)	Sa(T=1.0) (cm/sec^2)
TWK1	59.526	179.6	277.8	272.9
KAU	27.289	123.5	375.4	134.5
KAUP	26.683	156.4	347.1	167.2
SCK	92.914	118.3	270.9	109.1
SPT	29.588	90.7	275.1	144.3
SGL	35.085	81.5	204.0	157.9
CHN3	75.323	74.9	187.9	44.6
SSD	39.180	74.6	173.4	35.8
SCL	90.951	70.6	163.9	62.5
TAI2	71.410	64.1	134.8	48.8
SCZ	11.620	56.8	151.5	54.2
TAW	39.867	57.2	147.1	66.9
WCH	185.662	57.4		
LAY	114.711	59.2		

pressive strain inside the accretional wedges. However it needs more intensive studies to fully understand the seismological meanings.

The strong ground motion were well recorded by Central Weather Bureau (CWB) TSMIP array and are shown in Figures 2 & 3 as well as Tables 1 & 2 (Further information can be found on http://www.cwb. gov.tw). Figure 4 shows the response spectra of three RTD stations, which experienced the largest ground excitation (159.88 gal at Kenting), in the M_L6.7 main shock. The design spectrum of current Taiwan building code (TBC ’05) for Hengchun, the most damaged site, is also shown for comparison. The spectral acceleration is a little higher than that of the design earthquake for the TWK1 station, which is located at Hengchun and near the damaged area. A similar result of comparison of the largest aftershock (biggest PGA is 156.42 gal at Kaohsiung Harbor) of magnitude M_L6.4 is also shown in Figure 5.

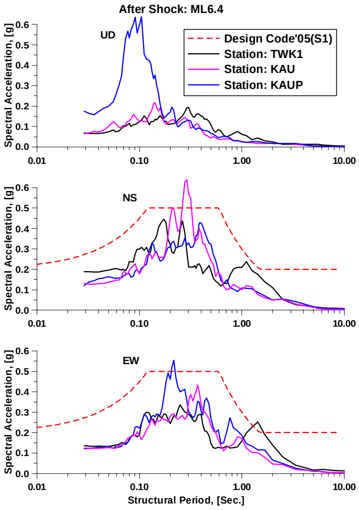


Fig. 4 The comparisons of response spectra (5% damping) at selected RTD stations in main shock (M_L6.7)

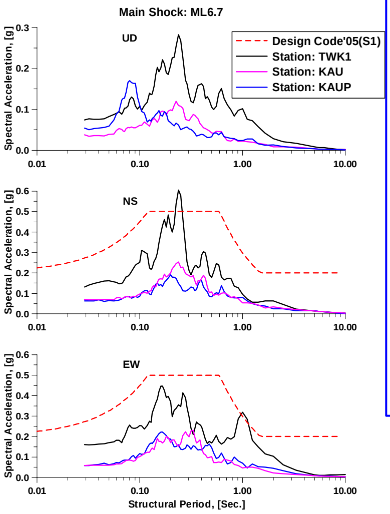


Fig. 5 The comparisons of response spectra (5% damping) at selected RTD stations in the largest aftershock (M_L6.4)

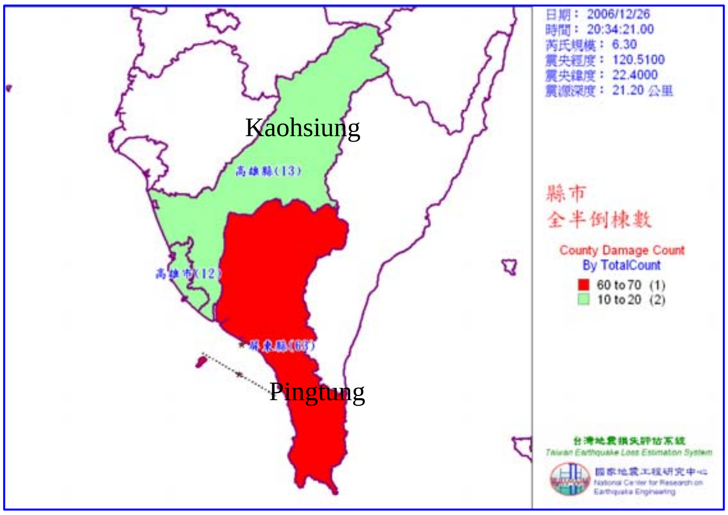


Fig.6 The map for estimated damaged house from TELES

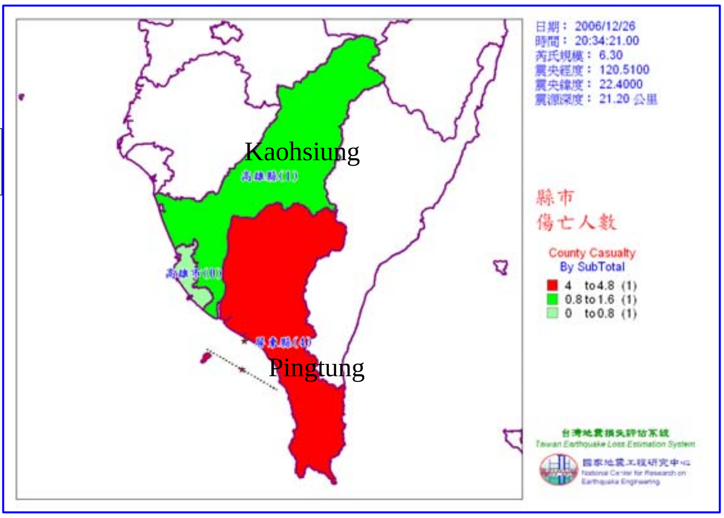


Fig. 7 The map for estimated casualty from TELES

Loss Estimation using TELES

Taiwan Earthquake Loss Estimation System(TELES), including an Early Seismic Loss Estimation (ESLE) module, was developed by the National Center for Research on Earthquake Engineering (NCREE) to integrate research accompli - shments on seismic hazard analysis, structural damage assessments and socioeconomic impacts in Taiwan. After receiving earthquake alerts from the Central Weather Bureau (CWB) of Taiwan, the ESLE module was automatically triggered and provided the estimated damages and casualties automatically in the form of maps and tables in 5 minutes. This information proves important for decision-making support systems and emergency response centers to properly dispatch rescue forces and medical resources to the right places. The estimation of TELES for this Dec. 26 Hungchun earthquake shows that there will be casualty in Pingtung County and damaged buildings in both Kaohsiung and Pingtung Counties (Figures 6-7). The actual damages are quite similar to the estimation of TELES in this earthquake.

Commercial/Residential Buildings

The collapsed furniture store was constructed in early 1980s. The brick walls were first erected and

Fig. 8 Back view of the collapsed furniture store

reinforced concrete columns, beam and slab were then constructed using the brick wall as part of the formwork (reinforced-masonry building). The total width and length of this building are about 7 m and 23 m respectively. Large openings for doors and windows are located at the street sides of the buildings for commercial demand. 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 open front and open space. This is the case of soft first-story damage mode. The floor plan of this collapsed 4-story mixed commercial and residential building is shown in figure 10. The first floor of this building is for commercial use and the rest of the floors are for residential use. There are a total of 15 columns. Along the long axis, the number of spans ranges from four to six. But the number of spans along the short axis just ranges from one to two spans, so that the redundancy is highly inadequate. Most of the brick walls are located at right side along the long axis, which makes the planar lateral stiffness asymmetric obviously. The photos of the collapsed building are shown in Figures 8 & 9.

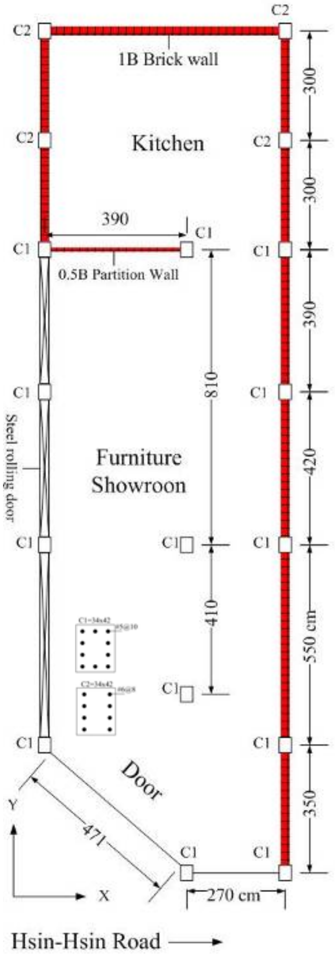


Fig. 10 Floor plan of a 4-story furniture store

In addition, some street-front residential buildings were also damaged severely. Figures 11 and 12 show the damaged features observed in this type of building. Brick walls and beams were seriously damaged, and the interior ground was cracked and bulged obviously.

School Buildings

Fig. 9 Front view of the collapsed furniture store

Fig. 11 The ground bulged inside the house

Fig. 14 Shear cracks were due to the short column effect

Fig. 12 The damage on the brick walls and beams

Fig. 13 The damaged column along the direction of the corridor

Fig. 15 The collapsed water tank on top of the school building

The damages to the school buildings were also significant in Pingtung County. In Taiwan, most school buildings at the primary and secondary levels usually lack integral planning, so the original structural system is easy to be seriously undermined. Most school buildings were constructed and expanded in a patchy way, which caused insufficient seismic resistance as an aftermath. The structural systems of school buildings have intrinsic defects. Classrooms are generally located side by side in a row. The plan of each classroom is about 10 m in width along the corridor and 8 m in depth perpendicular to the corridor. The corridor may or may not be cantilevered. The stiffness in direction perpendicular to the corridor is much higher than that along the corridor, and there is a strong tendency for damage to occur in this type of situation. In order to utilize the natural light and ventilation, windows and doors fully occupy both sides of the corridor. At the upper portion of the columns, they are constrained by the window frame made of aluminum or wood. The lower portions of the columns are constrained by the windowsill made of brick walls. Since the windowsill is rigid compared with the window frame, the effective length of the column is shortened. The shorter the column, the larger the shear force is. Therefore, the columns tend to fail in the shear mode rather than in the flexural mode. Figure 13 shows the column failure in shear mode while figure 14 shows a typical short column revealed the diagonal shear cracks and figure 15 shows the collapsed water tank on top of the school building.


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Fig. 16 Battlements of the old city wall at Hengchun were collapsed

Historical Site

The old city wall and gate tower of Hengchun were damaged as well. Several eaves of the gate tower were collapsed and a 30 meter long crack was found on the top of the wall. Around 15 battlements were collapsed, as shown in figure 16.

Non-Structural Elements

A chemical processing plant in the Fangliao area suffered from damage of several important components in the plant and will be out of operation for at least a month according to its managers. Damaged items simply described below included batch reactors, Counter Weight (CW) damage of elevators, and Automated Storage/ Retrieval System (AS/RS). Almost every reactor (about 8 to 10) supported on the third floor of a RC building was damaged. Each oval batch reactor, about 2 meters high, 1.5 meters in radius and weights 20 tons, was designed to penetrate the floor of a RC building and supported at the mid-height of the reactor on the RC floor (fig. 17). Below each reactor support there placed a load cell, providing vertical supports, to measure the weight of the

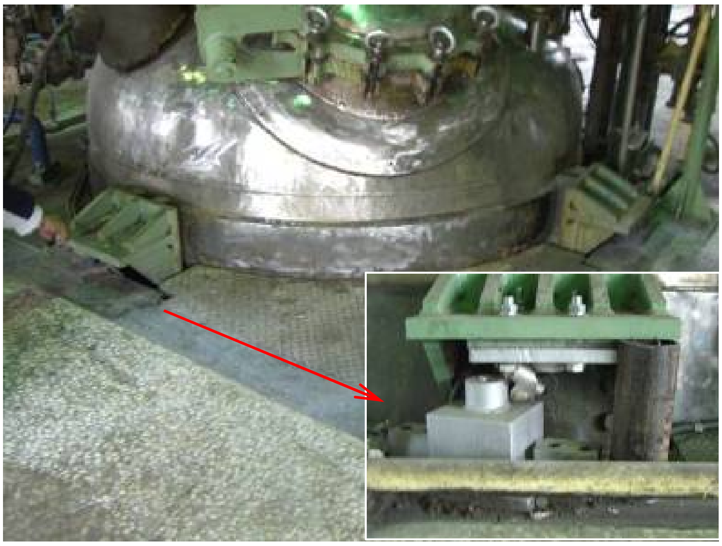

Fig. 17 Reactor with damage at supports

Fig. 18 CW iron plank fell in passenger cart

Fig.21 Ground cracks observed in school near Nanwan

reactor. In the earthquake, reactors shifted and bumped into the edge beams around the floor openings. All the load cells need replacement and reactors need realignment. Two elevators in a 4-story building suffered the drop out of CW iron planks fell into the passenger carts (fig. 18). The AS/RS racks are about 16 m tall and are said to have deformed to a degree that auto-picking cars can not perform its designed function. All the storage tanks need to be removed before any AS/RS repair work can precede. This posed a significant loss to the operation of the chemical plant.

Several hotels in the Hengchun suffered from water problems. One suffered water leakage from its water feeder pipes where pipes turn upright and caused the

Fig. 19 Heave of pavement near Nanwan

Fig.20 Crack observed near Nanwan

Fig. 22 Ground settlement and lateral displacement observed in school near Nanwan

flooding on the second and third floor in this hotel. The other hotel suffered from the loss of all six stainless steel water tanks on the roof that are broken on the steel skin and loss the capacity to contain water. Hospitals experienced little damage on both structural and non-structural elements. However, there were at least three reports of RO filter movement to cause plastic water pipe breakage. Several school gymnasiums experienced large area fall out of suspended ceilings.

Fig.24 Ground settlement, Soil liquefaction and building damages observed near Nanwan, the shells were found in the sand

Geotechnical Damages

There was no serious geotechnical hazard found this time, except slight ground surface cracks and permanent displacement of school buildings. The road surface with asphalt pavement near Nanwan was heaved and damaged, as shown in figure 19. Along a path near Nanwan, a series of parallel cracks (in the direction of NW to SE) on the road were observed, as shown in figure 20. Those cracks are parallel with distance 5-10 m apart, and the crack widths are about 3 to 8 cm. In the Hengchun Elem. School – Nanwan campus, some cracks were observed on ground surface, as shown in figure 21. Besides, ground settlements and horizontal displacements around the school buildings were observed as shown in figures 22 and 23. Furthermore, several signs of soil liquefaction were observed nearby (figure 24).

Lifelines

In general, lifelines sustained relatively little damage compared to houses. Steel transmission towers were mostly unaffected. Bridges experienced almost no damages. There are 2 gas leakages reported in Hengchun and 1 in Kaohsiung. Power shortages happened right after the earthquakes and totally around 3000 houses were affected. The electricity was restored on 23:00 that night. 12 elevator traps were reported in

Fig.23 Ground settlement observed in school near Nanwan

Fig. 25 The damage status of 5 undersea optic-fiber cables

Kaohsiung. The #2 reactor of the 3rd Nuclear Power Plant and Dalin Gasoline Refinery were shut down manually and are back to normal operation now. The telecommunication including line and mobile were down right after the earthquakes due to the mass demand. All systems were back to normal in 30 minutes.

More than 5 undersea telecom cables (APCN2, APCN1-North, APCN1-South, SMW3-South, and China-US, as shown in Figure 25), which are connected to China, Hong Kong, Japan, South Korea, Philippines, and Singapore, were snapped by the earthquakes and estimated to be fixed in one month (Table 3). All the international communication including internet services, international telephone, the international banking transactions, the stock market, currency trading, business communication to millions of customers were interrupted, and even the check-in counter of Taiwan's China Airlines are affected. Companies from South Korea to Singapore managed to partially restore the services by rerouting traffic through satellites and cables that were not damaged. Seven repair ships were working on repairing at the quake zone, revenue loss from the earthquake damage at about $3 million plus $1.53 million for repairing the cables was estimated, due to reporting by Chunghwa Telecom Co., Taiwan's biggest phone company.

Table 3 The Damages of undersea cables and their repair status

System	Damages	Cable Repair Status
RNAL ● Segment (Hong Kong - Busan) ● Segment (Hong Kong - Toucheng)	● The RNAL cable path between Busan and TongFuk was down at 12:43 26-Dec. (UTC). ● The other cable path, Hong Kong - Toucheng Taiwan was also down. ● It caused the Hong Kong being isolated from the cable system. The fault point of segment HKG - Toucheng is about 731km from Tong Fuk cable station.	● Cable Ship *Lodbrog* arrived at the repair ground in the afternoon of 28-Dec. ● It is expected to complete by 3-Jan. if everything goes smooth.
APCN System 1 ● Segment B17 (Hong Kong branch)	● The traffic on APCN system 1 was down since 18:15 26-Dec. (UTC) ● The fault is in the segment B17.	● Power reconfiguration was completed on 27-Dec evening hence the Korea - Japan and Taiwan were back to service. ● Cable Ship *Asean Restorer*, who is now in Singapore, is mobilized for the APCN SYS1 & SYS2 repair.
APCN System 2 ● Segment B5 (Taiwan Branch)	● The traffic on APCN system 2 B5 was down at 20:44 26-Dec. (UTC) ● It made the Taiwan node being isolated from APCN system. The fault location is about 920km from Toucheng cable station.	● The segment will be repaired after the System 1 work.
SMW3 ● Segment1.8 (Fangshan - BU4) ● Segment1.7 (BU3 - BU4)	● SMW3 reported that the traffic to Fangshan was lost since 12:25 26-Dec. (UTC) ● It was due to two faults appeared in SMW3 S1.8 and S1.7. The fault point of S1.8 is about 44km from FangShan cable station, whilst the fault point of S1.7 is 459km from Shantou cable station.	● Cable Ship *Retriever*, who is now in Philippine, is mobilized for the SMW3 repair.
APCN2	● The APCN2 S7 (Tanshui - Shantou) was re-	● Cable Ship *KPL*

● Segment 7 (Tanshui - Shantou) ● Segment 3 (Hong Kong - ChongMing)	ported down at 16:06 26-Dec. (UTC) whilst the S3 (Hong Kong - ChongMing) was also down at 18:01. ● It caused the traffic isolation between Southern Asia (Hong Kong/Singapore/ Malaysia/Philippine) to Northern Asia (Japan/Taiwan/Korea). ● The HKG to Singapore/Malaysia/Philippine traffic was still working fine in the southern Asia region. ● The fault point of S7 is about 905km from Tanshui cable station, while that of S3 is about 2091km from ChongMing cable station.	(Japan) will be mobilized for the repair of APCN2 S3 & S7
China-US ● Segment W1 (Shantou - ChongMing) ● Segment W2 (Spur to Fangshan) ● Segment S1 (Shantou - Okinawa/SLO)	● China-US segment W2 was isolated since 12:27 26-Dec. (UTC) ● Fault point is about 9.7km from FangShan ● At 18:59, another cable fault developed on China-US segment S1, 502km from Shantou cable station. ● At 02:07 27-Dec., the segment W1 was also down that made the Shantou node being isolated from China-US cable system. ● The fault point is about 452km from Shantou cable station.	● Cable Ship *KDD Ocean Link* (KOL) will be mobilized for the repair of CHUS.
FLAG FEA ● Sub-System 8 (Hong Kong - Shanghai - Korea)	● FLAG FEA reported that the Sub-system 8 had suffered cable fault at 20:56 (UTC). ● The fault point is between Repeater 9 and Repeater 10 near Hong Kong.	● Currently no any repair schedule for the FEA repair.

(According to the information on http://www.hardwarezone.com/news/ by Francis Yeo)

Response and Insurance

The Emergency Operation Center (EOC) of Fire Bureau for Pingtung County was set up a few minutes after the main earthquake rocked the southern Taiwan while the EOC for Kaohsiung County was also set up around 21:00pm after the first aftershock. Besides, the Operation Command Center (OCC) was also set up in Hungchun and the rescue operation was in practice immediately after the building collapsed. The helicopter was also sent to Hengchun for disaster surveying and operation monitoring. The 3rd nuclear power plant and Mu-Dan Dam were contacted and reported no major damages. The reconnaissance team was formed by NCDR and NCREE with assistance from both National Pingtung University of Science and Technology and the Fire Bureau for Pingtung County, and was sent for surveying and investigation in the morning on Dec. 27th. Though there are some damages on houses and fires reported, no claims on residential earthquake insurance was reported since they were not seriously damaged or not covered by residential insurance (the collapsed building is belonged to a furniture store).

Soil-Gas Precursory Signals

Soil-gas variations due to change in stress field related to seismotectonic activity are well documented and are used extensively for seismotectonic studies, including fault tracing and seismic surveillance as a precursor. Several gases with different origins and contrasting behaviors in soil have been documented for characterizing a fracture network allowing degassing. However, these are thought to have a subordinated effect on gas leakage from deep fault-related features. Changes in subsurface radon concentration have been observed to precede earthquake occurrence and therefore radon has potential use in earthquake prediction studies. Due to its short half-life (3.83 days) and insufficient diffusion length, the distance traveled by radon is limited. So, radon may be carried by other fluids or gases like

CO_2 and may play important role in controlling the migration and transport of trace gases like radon towards the surface.

Soil-gas surveys have been conducted across the Hsinhua fault, to find out the regional activity of this fault system. During the surveys soil-gas samples were collected along the traverses crossing the observed structures. The collected soil-gas sample bags are analyzed for helium (He), radon (Rn^{222}), carbon-dioxide (CO_2), methane (CH_4), argon (Ar), oxygen (O_2) and nitrogen (N_2). The data analysis clearly reveals anomalous values along the fault. The consistency of this pattern confirms that soil-gas can act as a powerful tool for the detection and mapping of active fault zones. Before selecting a monitoring site, the occurrence of deeper gas emanation is investigated by the soil-gas surveys and is followed by continuous monitoring of some selected sites with respect to tectonic activity to check the sensitivity of the sites. A site is selected for long term monitoring on the basis of coexistence of high concentration of helium, radon and carrier gases and sensitivity towards the tectonic activity in the region.

A continuous monitoring station was established at appropriate place based on the earlier surveys and long term monitoring in the end of October, 2006 using radon detectors RTM 2100 along with carbon-dioxide detector. Preliminary results of the monitoring station shows that the site is good for earthquake monitoring and soil-gas variations have shown good correlation with impending earthquakes of 26th December, 2006 having local intensity of 4 (as shown in Fig. 26). The radon concentration shows variation around 40 kBq/m^3 with diurnal variation of 15-20 kBq/m^3 in the normal conditions. Radon concentration shows steady increase from 21st of November, 2006 and reaches to its maxima of about 80 kBq/m^3 on 3rd December, 2006, followed by decrease to its normal values of about 50 kBq/m^3. These trends of increase and reaching to normal values continue till final anomaly on 16-17 Dec., about 10 days before the earthquake. The CO_2 carries gas for the radon in the region also shows anomalous values on 16-17 Dec. Whereas thoron (Rn^{220}), another isotope of radon having very short life of 54.55 sec. as compare to radon (Rn^{222}), has also shown very high values from Middle November to Middle December. These high values of radon, thoron and CO_2 before the earthquake at monitoring station are the precursory signals of 26th December, 2006 earthquakes and it may be due to the stress building in the region before the main events.

The anomalous fluctuation of radon, thoron and carbon-dioxide emanating from the soil-gas may have resulted from stress-induced pore collapse and stress-induced micro fracturing. The observed effect could be attributed to a possible combination of the both. The occurrence of soil-gas anomalies are random and they precede main

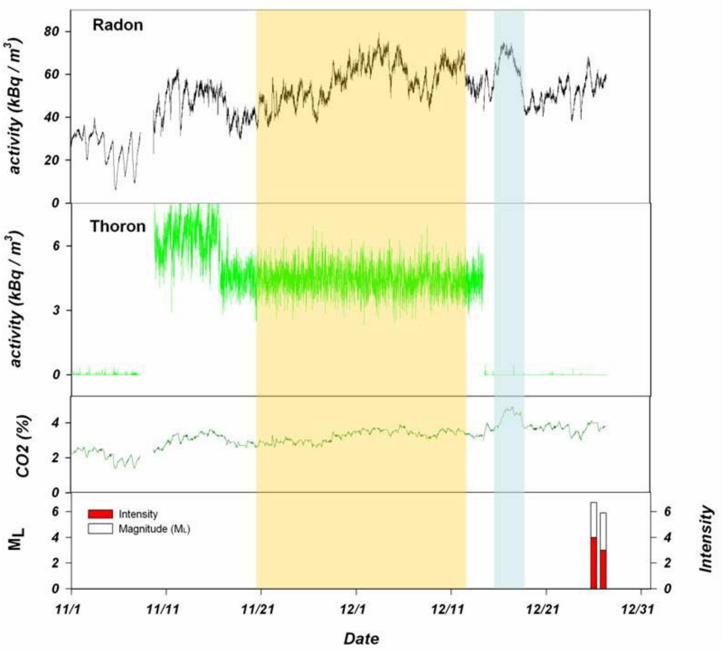

Fig 26: Variation of Radon, Thoron and Carbon-dioxide concentrations (Shaded areas represent the precursory signals in gases before the earthquakes) at earthquake monitoring station along Hsinhua fault in Tainan area.

shocks depending on the intensity which is a function of depth, epicentral distance, distribution of the stress field across the earthquake preparation zone and the main shock-slip orientation. The observed fluctuation may well be due to high frequency instantaneous stress changes and diffusive processes at depths of the earth's interior. Further, dilatation and compression effects due to stress changes are likely to cause the change in pore pressures coupled with micro fracturing, increasing the permeability of the host rocks reservoir leading to enhancement of gas concentration before the earthquakes.

This reconnaissance report will be constantly updated, please check NCREE website ***(http://www.ncree.org)*** *for further information.*

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