1999 Chi Chi Earthquake of Taiwan

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ABSTRACT: A devastating earthquake, namely, Chi Chi Earthquake (or Ji Ji earthquake in some literatures), with a magnitude of Ms = 7.6 (Richter Scale by USGS) or M_L =7.3 by Central Weather Bureau of Taiwan, struck central Taiwan at 01:47 on 21 September, 1999 (17:47, 20 September, UCT). Death toll reached 2,434 and there were 54 persons missing, 723 persons seriously injured and 11,306 minorly injured. In addition, there were 51,925 buildings col1apsed and 54,402 buildings seriously damaged. Presented herein are structural and geotechnical issues of the earthquake, including damages to bridges and buildings, landslides and liquefaction problems, etc. Also discussed are the recovery and reconstructions subsequent to the earthquake and the improvement made to the mitigation programs to prepare for future earthquakes.

1 INTRODUCTION

The Chi Chi Earthquake (M_L = 7.3 by Central Weather Bureau and Ms =7.6 by USGS) was the strongest earthquake with epicenter on the Taiwan Island in the 20th century. It is unique for its rupture length of 105 km and upheave of, upto, 9.8m. Strong shaking lasted for more than 40 seconds with a peak horizontal acceleration of 989 gals (east-west direction of Station TCU084) and a peak vertical acceleration of 716 gals (Station CHY080). Because of amplification effects, peak accelerations generally exceeded 100 gals in the Taipei Basin, which is more than 100 km from the epicenter.

In addition to the loss of lives, damage to buildings, infrastructures, and lifelines, etc., was wide spread. The earthquake and the damage made were extensively studied by professionals and researchers from Taiwan, Japan and the US, and a large body of data were collected, making it the best documented earthquake in the history. A series of reconnaissance reports were published by the National Center for Research on Earthquake Engineering (NCREE) of Taiwan and Multidisciplinary Center for Earthquake Engineering Research (MCEER) of the USA. A commemorate symposium was held in September, 2000 with 140 papers presented in four volumes, one each on science, geotechnical, structural and human aspects of the earthquake. Presented herein is a brief summary of the information given in these reports in an attempt to give an overview of the event and its consequences. This paper is not research-oriented and was prepared as a compilation of available information which might be of interest to structural and geotechnical engineers in a country with minor seismic activities.

2 THE EARTHQUAKE

As depicted in Fig.1, Taiwan Island is located at a complex juncture between the Eurasian Plate and the Philippine Sea Plate. Therefore, seismicity is extremely active on the island and major earthquakes were quite common.

The Chi Chi earthquake occurred at 1:47 of 21 September, 1999 (20 September, 17:47 UTC).

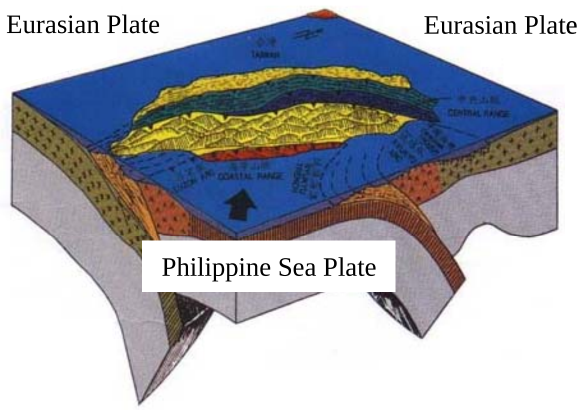

Figure 1. Plate boundary model of Taiwan

Figure 2 shows the locations of the epicenter and the contours of the levels of the ground shaking (Central Weather Bureau). The Taiwan Central Weather Bureau's Seismic Network (CWBSN) reported the earthquake information rapidly within minutes. The earthquake is believed to be associated with the Chelungpu Fault and the Shuangtung Faults, refer to Fig. 3 for geological section at the epicenter. These two faults are 10 km apart and subparallel to each other. They dip towards the east at high angles and are reverse faults with a significant left-lateral strike-slip component. The hypocenter at Chi Chi lies very close to the Shuangtung Fault and is located at a depth of 8 km, near the intersection of the two faults.

The number of aftershocks reached 10,252 as of 10 October, 1999 with six greater than magnitude 6.5. Even one year later, a few earthquakes of moderate magnitudes were still believed to be the aftershocks of the Chi Chi earthquake.

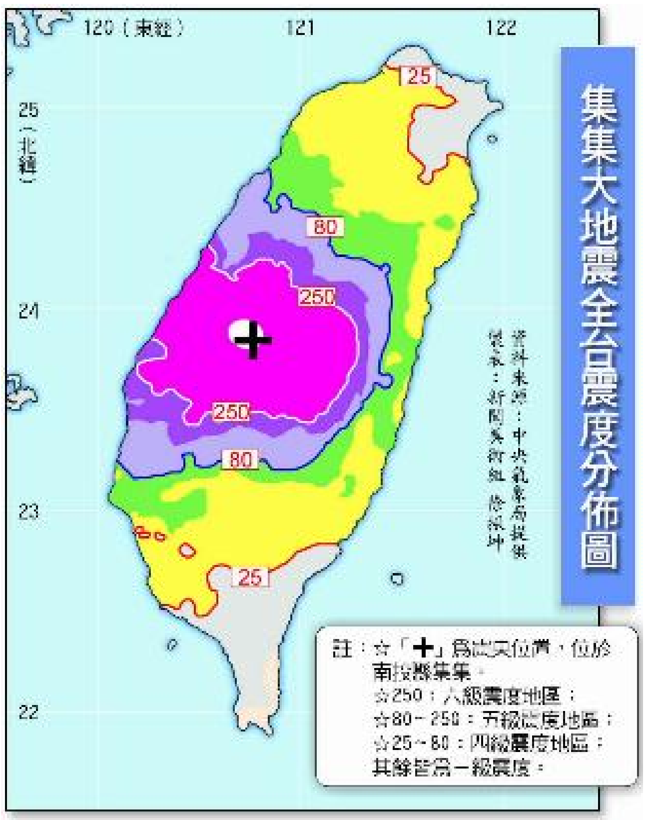

Figure 2. Epicenter and Contour of Levels of Shaking

As a direct result of this earthquake, 2,434 lives were lost, 12,029 people were injured, 51,925 buildings collapsed and 54,402 buildings suffered damages. This was Taiwan's worst disaster since the Hsinchu -Taichung Earthquake of April 1935, which measured M_L= 7.1 and took 3,325 lives (Central Weather Bureau). As of February 2000, the financial loss was estimated to be of an order of NT$362 billions (US$11.4 billions) by the Directorate General of Budget Accounting and Statistics of Executive Yuen.

3 RESPONSE TO EMERGENCY

Immediately following the earthquake, the government quickly established the Council for Disaster Response (CDR), convened by the Vice President Lien. Upon inspecting the disaster area, the Council recommended to the President to declare an emergency decree based on the Constitution. The central island was officially declared as disaster districts by the President in the evening of 25 September and the emergency decree was issued to empower the government to override some laws and statutes so resources could be quickly mobilized to meet urgent needs. The decree covered the city of Taichung and the five counties suffered the greatest damage and remained effective for six months from the date of issuance.

On 28 September, 1999 (one week after the disaster), the Executive Yuan announced the formal establishment of a restoration commission, namely, the 921 Earthquake Reconstruction Committee. Under the leadership of the Premier and the Vice Premier, thirteen senior government officers were appointed to head thirteen different task forces. Each task force was charged to handle problems within a particular subject area such as finance, education, environmental preservation, etc. Some task forces

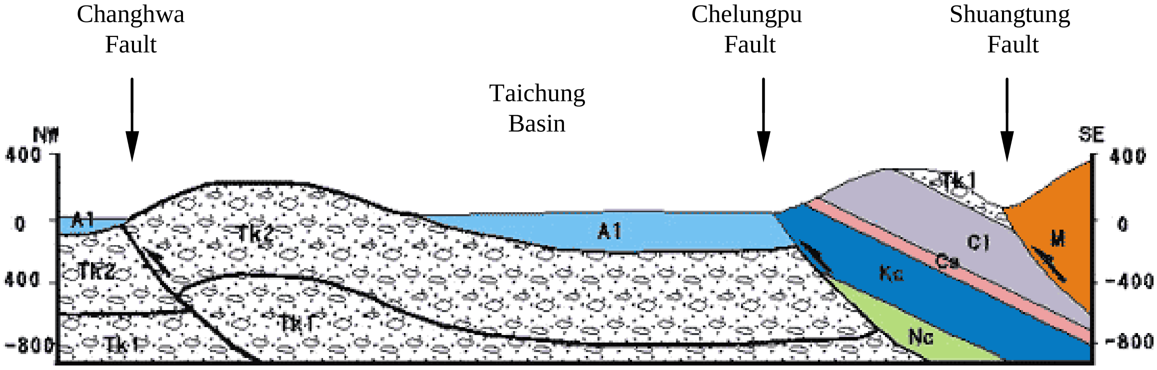

Figure 3. Geological Section at Epicenter

included, as their members, officials from the national and local government agencies working together to develop measures concerning restoration and reconstruction.

The public showed tremendous spirit as they worked together to save lives and help each other to go over the tragedy. Tens of medical teams were dispatched to the disaster areas by hospitals all over the island. Numerous charity groups and individuals offered their helping hands and massive supplies were rushed to the disaster districts by volunteers using their own vehicles. International assistance was particular touching. Japanese rescue team arrived at 5pm of the same day followed by 14 teams from other countries, totaling to 530 members and 38 dogs. Their efforts certainly won the applause from the local citizens.

The Ministry of Defense played a major role in the immediate emergency response and provided the major resources till local governments were able to regroup their forces. The emergency relief functions conducted by the military forces included shower stations, shelter centers, provision of security in the hard-hit areas, deployment of mobile medical teams, assemblage of temporary housing units, etc. Military forces were also deployed in demolition of severely damaged buildings and the emergency repair of bridges and roads to speed up reconstruction and recovery,

The civil engineering society did not overlook its responsibility to the community. NCREE was able to form several reconnaissance teams to collect first hand information and numerous researchers from local and international universities joined the activities voluntarily. Many of these teams arrived the scenes within hours after the earthquake. Several professional bodies were able to deploy practicing engineers from consulting firms to assist local governments to assess the conditions of buildings. Their judgments formed the basis for the demolition of dangerous structures and their observations become valuable sources of information for subsequent studies.

Within days after the earthquake, donations from all sources accumulated to NT$30 billions (US$ 1 billion). This fund was mainly used in humanity aids and has helped numerous homeless people. Part of the fund was used in construction of temporary housings and schools. This enables the disaster areas to recover in a rather short time.

4 CONSEQUENCES

Most of structures along the fault were non-engineered old structures constructed prior to the implementation of modern design codes. Even modern structures near the rupture were unable to resist the large ground movements and the intensity of shaking exceeded what was specified in the design code. This resulted in a pretty high damage rate of structures.

4.1 *Damage to Bridges*

There are approximately 1,000 bridges in the areas with strong shaking and 20% of them suffered damages to certain degrees. Twenty bridges were seriously damaged and required extensive repairs or had to be demolished and rebuilt. Many of them are located on Route 3 which is a major north-south highway running the length of Taiwan from Taipei in the north to Pingtung in the south. There are approximately 65 bridges on this route as it passes through Taichung and Nantou counties. Five of these bridges suffered collapsed spans (Photo 1) or cracked piers (Photo 2). Another five bridges on county and city highways experienced similar distress, including one cable-stayed bridge under construction. All these ten bridges are within 10km of the fault and most are within 5 km. Seven are located directly on the causative fault or on one of its branches. All are considered to be in the near

Photo 1. Bridge with Falling Spans

Photo 2. Bridge with Pier Damaged

field and thus subjected to intense ground motions both horizontally and vertically. The average fault dislocations were approximately 1.5m horizontally and 3m vertically.

4.2 *Damage to Buildings*

A large percentage of buildings that collapsed were non-engineered one-to-three story reinforced concrete frame structures constructed with brick infill partitions and exterior walls. Many of them had pedestrian corridors and open front at the ground floor (Photo 3). More than two dozen modern high-rise apartment buildings overturned or collapsed (Photo 4) because of inadequate design. Some of the buildings collapsed because of the so-called “short-column effects” as the spaces between columns were partly filled by partition walls (Photo 5). These partition walls trap the columns preventing the development of their normal flexural behavior over their height and allowing them to only deform over their free-height, i.e., the length of the column not surrounded by partitions. As a result, although the shorter length of the trapped column would make it possible to resist higher lateral forces before the flexural strength of the column is reached, the shear strength of a short column is often first reached and typical non-ductile shear failures ensue.

Photo 3. Building with Weak Ground Floor

Photo 4. Poorly Designed Modern Highrise Buildings

One of the significant features of the Chi-Chi earthquake was its large lateral and vertical displacements at surface. Buildings constructed across faults typically cannot survive the relative displacements that occur at their foundation due to fault movements. This type of failure was commonly seen along the fault (Photo 6).

Photo 5. Building Damaged Due to “Short-Column” Effects

Photo 6. Building Damaged by Ground Movements

4.3 *Damage to Schools*

Roughly, a total of 786 schools were damaged. Most of them were damaged because of the so called “short-column” effects described in Section 4.2 as the lower part of the space between columns were partially infilled by partition walls leaving the upper part open for windows (Photo 5). This type of damage in these reinforced concrete structures was rather common in the direction parallel to the exterior corridor outside the classrooms. The severity of damage to school buildings exceeded that of other structures due to primarily to the similarity of their design and construction. The eccentricity of most school buildings associated with cantilevered corridors at upper floors made the situation worse.

4.4 *Damage to Hydraulic Structures*

Damages to hydraulic structures were rather light. Of special interest is the Shikung Dam which is a concrete dam and was seriously damaged by ground movements (Photo 7). The fault directly ran through the foundation of the dam. The eastern portion of the dam was jacked up by 9.8m and the western portion of the dam was jacked up by only 2.1m, resulting in a differential movement of 7.7m.

Photo 7. Shikung Dam after Earthquake

4.5 *Damage to Critical Facilities*

Damage to critical facilities and lifelines, including hospitals, police and fire stations, power houses and transmission, etc., was widespread in central island. Nonstructural damage was found to be a major factor adversely affecting the functionality of major hospitals. The ones which were seriously damaged included Chritian Hospital at Puli, Veterans Hospital at Puli, and Shiu-Tuan Hospital at Tsushan. It was fortunate that fire broke out at only a few places and the consequence was relatively minor in comparison with those observed in some of the previous earthquakes in which fire was the major cause of casualty and financial losses.

4.6 *Damage to Power System*

The earthquake severely impacted the power system. With more population and less electricity generated, the northern half of the island relies on the southern half of the island for power supply. A significant number of transmission towers were seriously damaged causing failure in transmission of electricity from the south toward the north. Worst of all, Chung Liaw switchyards which is right at the junction of two trunk transmission lines was seriously damaged and, as a result, the northern island suffered a power outage for more than a week. The rationing of electric power to industries was finally lifted on 5 October and the rationing to residential users was lifted on 10 October.

The power failure severely impacted the industrial output as many factories were shut down because of outage of power. For example, Hsinchu Industrial Park which situates about 110 km from the epicenter and houses approximately 239 high-technology firms was seriously affected. In order to minimize the impact to economy, priority was given and power to this park was restored to full capacity on 25 September, four days after the earthquake. Even so, loss was estimated to be around US$400 million, most of which incurred at the semiconductor and silicon wafer production facilities.

5 GEOTECHNICAL ISSUES

Geotechnical hazards as a result of the earthquake included landslides, soil liquefaction, and foundation failures and were rather widespread.

5.1 *Liquefaction*

Soil liquefaction was the most dramatic in Yuan Lin Town in Changhwa County with an area of near 60 square kilometers seriously affected. More than two hundreds of dwellings were either destroyed or were damaged beyond repair. Most of the dwellings destroyed were poor single-story houses made of bricks or adobes. Modern buildings performed rather well and suffered only tilting with little structural damage (Photo 8). Sand boils were found only at locations at which the clay cover is either too thin or totally missing. At locations where the clay cover is thick, no surface features could be related to liquefaction except that ground subsidence led to settlements, up to a meter or so, of a few buildings.

At a nearby ground motion monitoring station (Station TCU110), a peak acceleration of 187 gals was registered. An extensive investigation program was carried out to unveil the ground conditions for the purpose of studying the mechanism of liquefaction (Ueng, Lin and Chen, 2001; Lin, Ueng, Chen and Huang, 2000). It included borings and penetration tests at 95 locations. Based on the studies, it was found that Seed's evaluation method as well as the associated liquefaction evaluation curve fitted the field data quite well.

In Nantou, a section of levee along the Maolo River was seriously damaged as a result of liquefaction. The monitoring station (TCU076) at a distance of 15km away recorded a peak acceleration of 420 gals and strong motion lasted for 41 seconds (Lin, Lai, Lin and Hseih, 2000). Liquefaction was found to be limited within depths of 4m to 8m. There was no indication of

Photo 8. Foundation Failure Due to Liquefaction

liquefaction in the underlying gravel layer. Post-liquefaction settlement ranged from 5cm to 26cm. According to the Seed Simplified Procedure, the critical peak acceleration that would lead to liquefaction would be about 0.29g.

In Wufeng which is within 1 km from the Chelungpu fault., liquefaction resulted in lateral spreading at four locations along the Koniaokeng Creek (Chu, Hsu, Lay and Chang, 2000) and damaged a few low-rise structures (Photo 9). A nearby monitoring station (TCU065) measured peak acceleration of 774 gals in the east-west direction, 563 gal in the north-south direction and 257 gals in the vertical direction.

Liquefaction at Taichung Port, which is located about 55 km northwest of the epicenter, damaged 4 of its 45 docking wharves. The port was built on a reclaimed land in four stages. The hydraulic fill behind Wharves 1 to 4 are retained by caissons which sit on a thin layer of cobbles and boulders. During the earthquake, the loosely dumped sands behind the caissons were liquefied and sand boils occurred all over the places (Chen and Hwang, 2000). Sands erupted from the ground can be found as far as 150 meters from the waterfront. Due to liquefaction, the caissons moved seaward by 1 meter on an average and the backfill behind these caissons settled by about 70cm. Due to the outward movements of the caissons, gaps were created at the interlocks between caissons and permitted the materials behind the caissons to be washed away by tides resulting in cavities of, up to, 30m in diameter and 4m in depth (Photo 10).

The nearest seismology station located at a distance of 4.7 km southeast of the Port registered a peak acceleration of 165 gals in the east-west direction and 152 gals in the north-south direction. The vertical component of the ground motion was small. Analysis indicates that this magnitude of ground motion would not be able to trigger the sliding of the caissons and the movements of the caissons must be the result of liquefaction of the backfill (Chen and Hwang, 2000). It is worthy of mentioning that the rest of wharves were retained by sheet piles and suffered no damage.

Photo 9. Building Damaged by Lateral Spreading

Photo 10. Damage to Taichung Port Due to Liquefaction

5.2 *Landslides*

There were thousands of landslides in the mountainous terrain within and adjacent to the epicentral area. A total of 436 scores of slope failure were investigated and documented in the reconnaissance report coordinated by NCREE. The Bureau of Water and Soil Conservation reported more than 2,300 items of variation based on the SPOT satellite photos taken before and after the earthquake (Ueng, Lin and Chen, 2001).

Nearly all of the slope failures are located to the right of Chelungpu fault, i.e., on the hanging wall, and most slides were relatively shallow slips in residual soils, typically involving depths of 1 to 5m. A massive slope failure involving 120 million cubic meter of debris occurred at Tsao-Ling. Twenty percents (about 25-million cubic meters) of the sliding mass dropped into the valley of the Ching-Shui River and blocked the flow causing flooding of the upstream valleys (Lin, Wang and Chen, 2000; Hung, 2000). Most of the sliding mass (of about 100-million cubic meters), and 39 people who lived behind the crest of the dip slope, flew over the Ching-Shui River, and landed on the other side of the river. Thirty two people were killed and 7 survived after the sliding-flying-landing process. Air-blast or release of compressed air cushion under the sliding mass is believed to be responsible for this abnormal phenomenon (Hung, 2000).

The debris blocked the river and formed a reservoir behind. As the water in the reservoir rises, there is the potential of overtopping the landslide dam and causing catastrophic flooding downstream. To ease the crisis, the plugged section of the Ching-Shui River channel was modified to allow for smooth and safe passage of the overflow. Check dams were also constructed in the downstream sections of Ching-Shui River for safeguarding the people and the lands from being smashed by possible debris flow due to sudden break of the landslide dam.

6 RECOVERY

Soon after the situation was under control, the government turned its attention to the reconstruction in the disaster areas. The recovery proceeded at a rather quick pace. Electric power was back within 2 weeks on the entire island and within 3 months all the damaged bridges were either repaired or replaced by new ones of which some are temporary structures.

In areas which experienced liquefaction, underpinning and grouting were carried out to remedy tilted buildings. Low-rise buildings, up to 4 stories, were successfully made right by underpinning and mid-rise buildings, up to 7 stories, were successfully made right by grouting.

The Council for Economic Planning and Development (CEPD) prepared a five-year reconstruction program, namely, the Post-Earthquake Reconstruction Plan (PERP), which received the Executive Yuan’s approval on 9 November, 1999. A governmental agency, namely, “921 Earthquake Post-Disaster Recovery Commission”, was formed on 1 June, 2000 to undertake the responsibility of reconstruction and a budget of 200 billion NT dollars (7 billion US dollars) was allocated for the three years to come. The use of the fund is supervised by central government and by civilian organizations as well to ensure that the fund is used to the maximum benefits of people.

7 MITIGATION PROGRAM

The Chi Chi earthquake certainly increases the awareness of people of potential threat of earthquake and provides an opportunity for improving the preparedness for earthquakes in future. The government has allocated a generous budget to support researches related to earthquakes and earthquake engineering. The following are a few programs which have already been implemented or being implemented:

7.1 *Instrumentation and Monitoring of Ground Motions*

Under the Taiwan Strong Motion Instrumentation Program, there are more than 650 strong motion observation stations distributed and maintained by the Central Weather Bureau, Ministry of Transportation and Communications. About 70 percent of these observation stations were triggered by this earthquake. With 73 real-time monitoring stations spread over the island and directly connected to the Central Weather Bureau, the epicenter and the magnitude of the Chi Chi earthquake were determined in, as short as, 102 seconds, which is unprecedented in history. The Bureau is making further efforts to shorten this time to only 20 seconds (CWB, 2000). Any time shortened is significant in reducing damages and saving lives because warning can be issued in time for emergency prevention mechanism to be activated. For example, trains of rapid transit systems and high speed rails can substantially reduce their speeds if it is predicted that the shaking will exceed the safe level.

7.2 *Enhancement of Geological Information System*

Web geographic information system (WGIS) was extensively used in the investigations following the earthquake. When performing the reconnaissance, a standardized inventory format together with the input system was established by NCREE so that the information collected from field could be input to the database directly. The database was connected to the geographic information system for data management and further analysis, and development of thematic maps could be done accordingly. This enabled information from various sources to be compiled in the shortest time possible. Furthermore, because of its ability to display maps and graphics, GIS also enabled users of all ranks to comprehend information much more easily. The GIS systems were combined with satellite images and aerial photos to identify areas with large damage. The results were useful in the rescue operations and reconstruction.

Realizing the importance and the potential applications of GIS, efforts are being made by the government to centralize the information managed by various agencies so updated information can be readily available to all levels of government and various organizations. An ambitious program is to be implemented to prepare a GIS version of geological hazard maps for the entire island so potential risks can be assessed.

7.3 *Revision of Seismic Design Code*

Another major development resulted from the earthquake is the revision of criteria for seismic design of structures, particularly in areas in which ground shaking certainly exceeded what was specified. The entire island is now divided into three seismic zones with design peak acceleration upgraded.

7.4 *Emergency Response Programs*

Many lessons have been learned from this earthquake and the island is doubtlessly better prepared for the future. The government is now pushing for the expansion and enhancement of the hazard prevention system, which is not limited to earthquakes but also includes other types of natural hazards such as fire, flood, and debris flow. To enable studies to be carried out in advance and actions to be taken promptly in case of emergencies, databases are established to compile relevant information and to assess risks involved in various types of disasters. The most comprehensive program is the so called Haz-Taiwan which is an application software for simulating the scenarios of earthquakes. It was derived from HAZUS97 (Risk Management Solutions, 1997) which was developed and tested in the United States for the Federal Emergency Management Agency (FEMA) by the National Institute of Building Science (NIBS). The basic information to the program includes ground motions, soil map, liquefaction susceptibility map, landslide susceptibility may, water depth, etc. To assess the loss to incur, information such as distribution of population and buildings, locations of critical facilities including police stations, schools, hospitals and clinics, lifelines, is required. Attempts are being made to incorporate the information collected in the Chi Chi Earthquake to refine the analytical model adopted in the program.

8 ACKNOWLEDGEMENTS

The authors are grateful to all the authors and editors of the papers quoted herein.

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