Chapter 6. Concluding Remarks

When a city is located in area prone to earthquakes, every effort must be made to construct earthquake-resistant buildings and infrastructure. In reality, however, this is difficult, especially in developing countries where the need for urban development takes priority over disaster mitigation.

The Chi-Chi Earthquake struck central Taiwan with a magnitude of 7.3 at 17:47, September 20, 1999 (GMT), 01:47 AM, September 21 local time. The Chi-Chi earthquake occurred on the Chelungpu Fault, with an epicenter located at 23.85N and 120.81E, north of Chi-Chi in Nantou County, with an epicentral depth of 6.99km. Similar to other cities throughout the world, the major cause of death among the 2300 fatalities and the major cause of physical damage were the collapse of buildings; approximately 8700 were destroyed.

This EDM report reviews and summarizes the earthquake fault, ground motions and structural and geological damages resulting from the Chi-Chi earthquake, including analytical data obtained by on-site reconnaissance and satellites imagery. Our analytical research is compiled in this research report on the 1999 Chi-Chi Taiwan earthquake. The discussion on each research item has been summarized in this chapter. The remarks concluding each topic from the previous sections create an overall review of this report.

Chapter 2 Earthquake and Damages

Characteristics of strong ground motion

We investigated the characteristics of earthquake strong ground motion records using 420 three-component records of the Seismological Center of Central Weather Bureau of Taiwan to calculate the strong motion indices, the PGA, PGV, I_{JMA}, and SI (listed in Appendix). Near the Chelungpu fault, the velocity time histories revealed a large pulse-like motion lasting longer than 3 seconds was observed in the direction of maximum amplitude. This pulse–like motion represents the cumulative effect of the seismic pressure radiating from the fault rupture.

At recording stations along the northeast hanging-wall side of Chelungpu fault, the PGV reached levels of 384cm/s. In spite of these large PGV values, structural damages surrounding the instruments were not severe, due to a short pulse period at these stations. As PGV is influenced by the length of the pulse, it is not a reliable parameter to predict structural damage. I_{JMA} and SI values more accurately reflect the damage status than PGV in the case of the Chi-Chi earthquake.

To investigate the characteristics of near-fault ground motion in terms of their spectral contents, we calculated the acceleration and velocity response spectra for the maximal velocity direction for sixteen near-fault stations. The preliminary analysis suggests forward rupture directivity in the northern part of Chelungpu fault. A large pulse motion with a period longer than 5 seconds was observed in a direction almost normal to the fault. This directivity may have severe effects on long period structures; fortunately, no such long period structures were present along the Chelungpu fault when the earthquake occurred.

The reliable strong ground motion data obtained from the earthquake, with multiple near-fault records, enables a detailed, future study considering the source parameters such as the direction of slip on the fault, slip rate and the preexisting geological conditions as well as the forward rupture directivity effects.

Characteristics of damage to building and infrastructures

Over 17,000 buildings collapsed or were severely damaged in the earthquake. Approximately 90% were concentrated in Taichung City, Taichung County and Nantou County. The number of collapsed buildings greatly exceeded the number of severely damaged buildings. Municipalities such as Tungshih, Wufeng, Chungliao, Puli, and Chi-Chi were severely damaged. In addition, extensive building damage in Chungliao was debilitating to the citizens. Building damages were also observed locally in Taichung, Fengyuan and Tali etc.

The collapse of comparatively new, mid-height (approximately10-story) RC residential buildings were common. Although buildings surrounding this type of collapsed building suffered some damage, such as wall cracks, many of the neighboring buildings sustained very little damage.

In the areas where the surface faulting was seen, such as Shihkang, Fengyuan, Takeng in Taichung City, and Wufeng, the fault displacement caused the inclination or collapse of multiple buildings. Buildings located a few meters from the fault line, however, were often not damaged. In Taiwan, public paths called "Qi Lou", buildings whose first floors are set back with the overhanging upper floors partially supported by outside columns, allow pedestrians to avoid strong sunshine and rainfall. Many of the RC buildings damaged by the earthquake had this "Qi Lou" design. The pillars on the front of the building collapsed, causing the buildings to incline or collapse by loosing the columnar supports.

First-story damages were also observed in new mid-rise and high-rise residential buildings. Mid-story collapse, seen in the 1995 Hanshin-Awaji (Kobe) earthquake, was infrequently observed in this earthquake. Old wood-frame buildings and structures with earthen walls also sustained substantial damage.

Much of the social infrastructure in the disaster area, including bridges and lifeline facilities, only suffered minor damage. Most of the severe damage was associated with a large ground offset induced by fault rupture and strong seismic motion near the epicenter. Collapsed girders, resulting from the foundation movement, characterized the major bridge damage along the fault. Rigid structures along the fault, such as dams, suffered severe structural and functional damages; because the inflexibility of the structures did not permit the large ground displacement induced by the fault rupture. The pipelines along the fault failed due to shear loading induced by the fault offset. These damages were observed over a small, local area across the fault rupture; structures sufficiently distant from the fault rupture suffered only minor structural damage.

Recent seismic design code makes it difficult to design a flexible structure, capable of following a large fault offset. Further investigation is necessary to predict the location of faults and the possible fault offset on the ground surface; in addition, the development of new flexible structure could also reduce earthquake damage in the future.

Liquefaction

Ground surveys of Taichung Harbor, the central part of Nantou city, and the Yuanlin district, were performed to investigate the damage to buildings due to soil liquefaction during the 1999 Chi-Chi earthquake, Taiwan. The following concludes the results of surveys in the three districts:

1) Taichung Harbor was heavily damaged due to liquefaction of the subsurface soil.
2) In the North terminal of Taichung Harbor, a large horizontal displacement of caissons caused the settling of backfills.
3) In the North terminal, fine sand layers up to a depth of 6 m were liquefied during the earthquake.
4) Soil liquefaction resulting in the Settlement and inclination of tall buildings (over about four-storied) occurred at the sites where the water table is shallow.
5) Subsurface soils in Yuanlin district (near Yuanlin station) moved various directions during or after the earthquake.

Chapter 3 Disaster Management

Damaged area estimation

We applied our proposed method estimating the damaged areas to the Chi-Chi Earthquake Disaster. Due to heavy clouds around the onset day of the earthquake, we estimated the pre-event image from the Stable Lights Data and the regression curve representing the relationship between digital numbers of observed image and Stable Lights Image. It is necessary, however, to compare the estimated results with a measure of real damage, such as power outage distribution, to demonstrate its validity. In addition, a post-event image, also needed for damage estimation, is difficult due to the influence of clouds on the post-event images. We continue further investigations and examinations to devise a robust and reliable estimation method under various conditions.

In the 1999 Kocaeli Earthquake Disaster, Turkey, the estimated damage result was available three weeks after the earthquake. In the 1999 Chi-Chi Earthquake Disaster, ten days since the onset of the earthquake disaster were needed to disseminate the final results; these delays are too long to direct emergency actions. The entire process must be reduced to less than 24 hours after the disaster event by establishing a proper procedure of analysis and dissemination.

Disaster response

Disaster response in the earthquake disaster was performed based on the previous experience of the Hanshin-Awaji (Kobe) earthquake disaster. Many institutes could benefit from study of disaster management in Taiwan; disaster relief in Taiwan may aid the improvement of Japanese disaster management. Continuous survey of the progress of Taiwan in prevent earthquake disasters would be beneficial.

Chapter 4 Damage Detection from the Air and Space

Extraction of the Areas of Slope Failure using SPOT Images

We examined the reflectance characteristics of slopes to estimate slope failure due to the earthquake from SPOT/HRV panchromatic images taken before and after the earthquake. The striping of vegetation revealing the bare soil beneath results from strong ground shaking. In the post-event image, this region of slope failure gives high digital numbers in comparison to other mountainous areas. We calculated the normalized, DN difference between the pre- and post-event images to emphasize the DN change. We created a pseudo color image to determine the areas of the greatest slope failure. The extracted damage distribution agreed with the large-scale slope failures identified by the on-site damage survey performed by the Japanese Geotechnical Society. Several additional small areas were also identified by this estimation method; it is necessary to confirm the presence of slope failures/landslides in these areas through more detailed damage survey data.

Automated Damage Detection using Aerial HDTV

We utilized aerial HDTV images to observe the hard-hit areas after the earthquake. We then applied the automated damage detection method, developed for the Kobe earthquake, to those images. This automated damage detection method defines the characteristics of building damage based on hue, saturation, brightness and edge intensity. Using the threshold values of these parameters, areas were classified into damaged and undamaged pixels; the texture analysis, as defined above, was introduced to these pixels to identify the damaged buildings.

The extracted damage distribution by the proposed automated method agreed well with visual inspection of the images. Although the examples used here were limited, the possibility of early damage extraction using aerial HDTV images for automated damage detection will be highly useful in the future. Further case studies are necessary to establish more general methodologies and threshold values to create a widely applicable technique.

Chapter 5 Simulation of Damage Process

Quaywall damage

We investigated the process by which quaywalls were damaged based on the pattern of damage. We performed a liquefaction analysis of the soil-structure system to understand the process by which the caisson quaywall was damaged in Taichung Harbor. We examined the extent of liquefaction behind the quaywall resulting in the permanent movement of the quaywall. The numerical simulation reproduced the liquefaction of backfill sand and the seaward deformation of the caisson quaywall. Further investigation of the soil parameters including the foundation seabed soils will allow a more accurate prediction in the future.

Buildings

The analytical study of a HFW apartment building was used to investigate the seismic behavior of a building being subjected to the input of the near fault acceleration records obtained from the earthquake utilizing a three-dimensional nonlinear model for the response analysis. The response analysis indicated that although the building is resistant to the moment in the frame direction, shear failure occurs in the shear wall direction even though the load carrying capacity meets the design requirements of the Japanese design code. Severe damage, however, may result from ground motion with a PGA over 0.7 G. The results seen in this disaster clearly demonstrate the collapse of buildings in response to very intense ground motion with a PGA over one G.

The EDM hopes this technical research report will be of great interest and use for research and practical application before, during and after a hazardous earthquake. The analytical results on strong ground motion, damage detection, damage evaluation and assessment, and disaster management included in the report may be utilized for earthquake disaster mitigation as described herein.

We would like to express our sincere thanks to Professor Chin-Hsiung Loh, Director of the National Center for Earthquake Engineering Research, Taiwan.

We are grateful to Mr. Ming-Tuh Hsieh of the Research Center of Harbor and Marine Technology for his valuable comments on the construction of caisson quaywalls in Taichung Harbor. We would also like to thank Professor Akenori Shibata and Professor Yoshiaki Nakano, the leader and the secretary of the AIJ Reconnaissance Team, to Dr. Satoshi Tanaka of DPRI, Kyoto University, and to Dr. Osamu Murao of IIS, Tokyo University.

The DMSP/OLS images used in this study were provided by the National Oceanic and Atmospheric Administration's National Geophysical Data Center (NOAA/NGDC). We wish to thank Dr. Haruhiro Fujita and NOAA/NGDC for their cooperation. The SPOT/HRV images used in this study are owned by SPOT Image. HDTV images were provided by the Japan Broadcasting Corporation (NHK).