ADVANCEMENT OF EARTHQUAKE MITIGATION IN TAIWAN

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Abstract. The 1999 Chi-Chi Taiwan earthquake is the most disastrous in recent decades that was also a significant watershed moment for engineering seismology development in Taiwan. After this earthquake, the National Center for Research on Earthquake Engineering (NCREE) invested many resources to develop the technologies for earthquake disaster prevention. Three examples with different aspects are presented in this paper. The first one is to clarify how large the seismic threat is by a novel probabilistic seismic hazard analysis (PSHA) procedure. The detailed and precise information about the seismic hazard is the foundation of the seismic design and disaster prevention. Secondly, the school buildings damaged by the 1999 Chi-Chi earthquake highlighted the problem of their fragility. The seismic performance of school buildings was comprehensively improved by seismic evaluation and retrofitting to protect students. Finally, the advanced earthquake early warning system and structural safety monitoring system can reduce the loss of life and property when an earthquake happens.

Keywords: earthquake engineering, seismic hazard, seismic retrofitting, earthquake early warning

Introduction

The National Center for Research on Earthquake Engineering (NCREE) was established in 1990 and completed the construction of the laboratory and research building in 1998. The main purpose was to improve the technology of earthquake engineering through the earthquake simulator laboratory (Shaking table, et al.). The application oriented researches in NCREE, including earthquake-resistant problems to be solved theoretically or experimentally, have been carried out to develop novel earthquake engineering technology.

In 1999, a devastating earthquake with magnitude M_W7.6 attacked centrally. The 1999 Chi-Chi earthquake was the most disastrous earthquake in Taiwan in recent decades. Geologically, Taiwan lies between the Philippine Sea Plate and the Eurasian plate. Tens of thousands of earthquakes occur in Taiwan every year, with about one thousand felt earthquakes. Every 10 to 15 years, there has been a disastrous earthquake that killed more than 100 people in Taiwan. Therefore, people in Taiwan have to live with earthquakes. It is impossible to eliminate earthquake disasters but we can mitigate it by progressions of earthquake engineering. In the last two decades, the massive and high-quality strong-ground motion data of the 1999 Chi-Chi earthquake has contributed to the developments of seismology, earthquake engineering, and disaster management in Taiwan. It also has benefited the rapid development of disaster prevention technologies, especially for seismic hazard assessment, seismic retrofit of buildings, and earthquake early warning, et al. In this paper, the advancements of three topics for mitigating earthquake disasters in Taiwan are introduced.

Probabilistic seismic hazard analysis

Taiwan's extremely high seismic hazard has to be seriously considered for the seismic design, building codes, and disaster preventions. However, most of the inputs for detailed and precise seismic hazard analysis, such as the ground motion characteristics, site effect, near-fault effect, long-period pulse effect, etc., are insufficient before the 1999 Chi-Chi earthquake. The plenty of high-resolution strong motion data recorded by the Taiwan Strong Motion Instrumental Program (TSMIP) made this earthquake became a turning point. NCREE invested many resources and made a big leap in developing the probabilistic seismic hazard analysis (PSHA).

Since 2000, NCREE cooperated with the Central Weather Bureau (CWB) to construct Engineering Geological Database for TSMIP (EGDT) to evaluate P, S-wave velocity and provide geology description information from drilling for strong motion stations. Up to 2012, the EGDT has set up around 450 sites that provide detailed site information such as Vs30 (average shear wave velocity for top 30 meters) for site classification, PSHA, and seismic design. Meanwhile, various technics, databases, and models of PSHA were progressively studied and renewed. Based on the more and more understanding of ground motion characteristics and seismic hazard, the seismic design code (Fig. 1) in Taiwan was also revised several times to consider new seismic zones, micro-zonation of Taipei Basin, and near-fault factor, etc. In 2016, NCREE hosted the Senior Seismic Hazard Analysis (SSHAC) project Committee Level III to reevaluate the seismic hazard of the nuclear power plants in Taiwan. This project helped us comprehensively improve the PSHA procedure with the experts at home and abroad. Now, the new EGDT site database includes Vs30, Z1.0 (depth of velocity reached 1.0 km/s), and kappa (high-frequency attenuation for FAS) for around 850 TSMIP stations [1] following global tendency in site classification for PSHA and seismic design. The newly developed Ground Motion Prediction Equation for Taiwan was developed based on the local ground motion database, American NGA experiences, and novel regression for truncation [2]. In addition, the seismic source characteristic model for the whole of Taiwan was constructed by cooperation with the experts of earth science. The PSHA can take advantage of all the achievements to expose potential seismic threats and discover the potential hazard and risks in Taiwan.

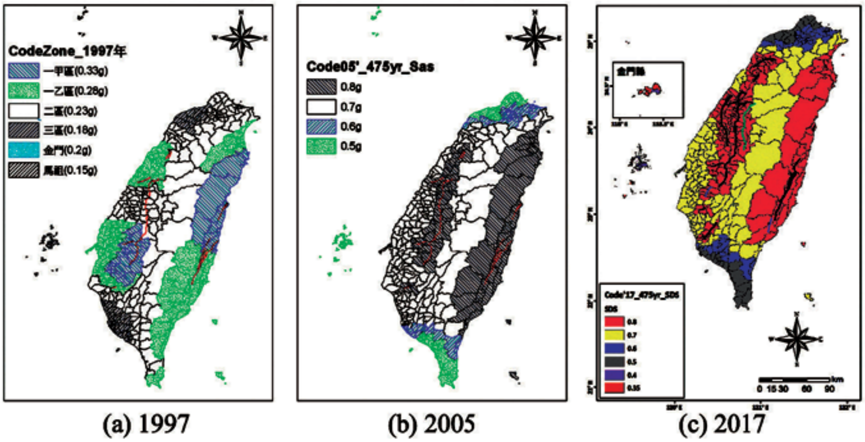

Figure 1. *Progression of the seismic design code for buildings in Taiwan*

Seismic retrofitting RC school buildings

The 921 Chi-Chi earthquake demonstrated that the safety level of school buildings in Taiwan is of great concern. During this earthquake, more than half of the school buildings in Nantou County were either partially or fully destroyed. Therefore, it is without a doubt that the seismic capacity of the school buildings in Taiwan should be a great concern and that the seismic capacity of the school buildings needs to be urgently improved through retrofitting. However, there are 3,763 public elementary, junior, and senior high schools (including vocational schools) in Taiwan and over 27,000 school buildings. Such a large number of buildings would easily exhaust the available funds if no economically effective method to follow.

From the reconnaissance of the 921 damaged school buildings, typical school buildings of Taiwan were mostly damaged by the failure of vertical structural members on the first floor and led to the collapse of the buildings along the direction of the corridor. Therefore, increasing the number of vertical structural members, or improving the strength and ductility of existing columns are effective methods of retrofitting. Traditional retrofitting methods, such as the RC column jacketing, the steel jacketing, and the addition of wing wall, are selected due to economic reasons. Those selected retrofitting methods were verified through the in-situ school tests. Fig. 2 illustrates several traditional methods of retrofitting applied to the buildings [3].

The Taiwan government allocated a budget of around TWD98 billion (1USD 30TWD) to upgrade, from 2009 to 2022, the seismic capacity of public elementary, junior, and senior high school buildings. NCREE entrusted by the Ministry of Education, established a Project Office for Seismic Upgrading of School Buildings to provide technical and administrative assistance to the project. In terms of technical assistance, NCREE provided methods for the school buildings' seismic evaluation and retrofitting. In terms of administrative assistance, the Project Office established operation specifications, gave seminars, popularized good retrofitted examples, and established a data bank.

Currently, the completed retrofitting constructions have reached 6,526 school buildings. At the end of 2022, the retrofitted school building can reach a number of 7,852, which is approximately 1/3 of the total public-school buildings in Taiwan. It is hoped that, by seismic evaluation and retrofitting of school buildings, the general public of Taiwan would understand the importance of seismic retrofitting. This work may be continued and extended to other existing buildings to create a more secure homeland.

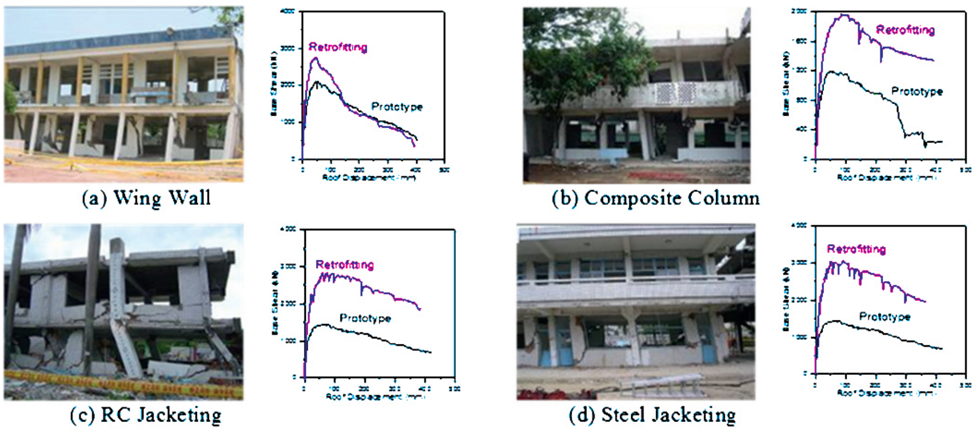

Figure 2. *Experimental Verification of Retrofitting Measures by In-situ School Tests.*

Development of the earthquake early warning and structural safety monitoring system

NCREE has developed an on-site earthquake early warning system (On-site EEWS), which can detect the first coming P-wave of an earthquake and estimate the strength (Peak Ground Acceleration, PGA) of following strong wave in 1–3 seconds. The On-site EEWS is composed of the sensing (seismic sensors), processing (PGA estimation of the following S-wave), and action (warning people, relay control to mitigate the seismic loss). Multiple sensors are applied in various locations to mitigate false alarms. After years of testing, in the 2016 Mei-Nong earthquake, one on-site EEWS in the blind zone of the conventional EEWS (epicenter distance 38km) successfully issued an alert 5.34s before the maximum shock. Due to the outstanding performance, the on-site EEWS had gradually increased to 94 set all around Taiwan. And the accuracy of prediction intensity (±1 level) was more than 98% from 2016 to 2020.

In 2016, the CWB announced the regional EEW service for the public in Taiwan. With the growth of the application of on-site and regional EEW, NCREE got a mission from the government to combine the regional and on-site EEW to be the "Hybrid EEW", establish the cloud service (B2B) for the industry and develop various EEW-automation application with the industry. The final goal is to establish an industry of seismic disaster reduction. Until 2020, more than 3500 schools, 21 fire departments, 12 buildings, 8 semi-conductor plants, 2 science parks, 2 hospitals, 2 exhibition halls, one stadium, and the Taiwan High-Speed Rail had applied the earthquake early warning system. The earthquake alarm transmits to various devices via the internet in 2 seconds. In these demos, people were notified before shake by alarm sound and flashlight, gas vale automatically closed, elevator stop at the closest floor and evacuate users, the spotlight indicates people the safety shelter position, production line soft stopped (for rapid recover). In the 2019 Hualien earthquake, the Hybrid EEWS showed its great performance again. From 6~14 seconds after the earthquake occurred, the on-site EEW issued a warning for the close-epicenter areas with the earthquake wave propagated. On the 14^{th} second, the regional EEW issued a warning for the whole country. It showed the great advantage of the Hybrid EEWS, the on-site EEWS can help the close-epicenter area got a warning earlier, greatly reduce the blind zone of the conventional EEW.

With the development of the EEW application, people are also starting to think further if the structure is safe after the earthquake. From 2013, NCREE had cooperated with a few universities in Taiwan to develop the Structural Safety Monitoring System (SSMS). State-of-the-art technologies about structural health monitoring had been developed for decades. It is time for NCREE to integrate the sensors, monitoring system, and structural safety assessment in SSMS. The sensor arrangement was designed according to the structure feature, function, and cost. The monitoring system detects the earthquake and collects all the data, and multiple safety assessment methods from academics had been applied for comparison. The first demo system was established at the office building of the Central Science Park in Taiwan. From 2020, NCREE started to cooperate with the Central Weather Bureau to set up SSMS for 30 buildings. NCREE's new building was one of them. Fig. 3 shows the working flow of the SSMS. About one minute after the shake, SSMS will provide a fast report to show all the sensors recorded. 5~10 minutes later, multiple structural safety assessment reports will be generated to show the safety level of the structure and possible damage locations. It can greatly speed up the post-quake reaction, people will not have to wait on the street for the experts to check the structure, and the resilience can be increased. At the same time, all the data will be open to the academic, and more structural safety assessment methods can be developed and validated.

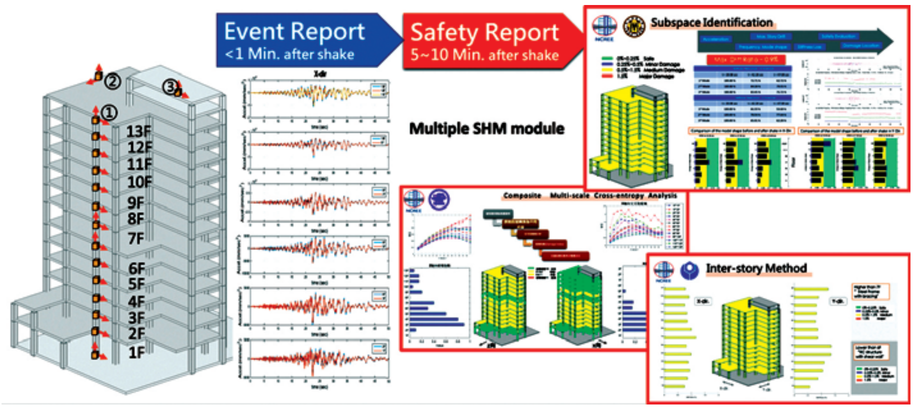

Figure 3. *The working flow of the Structural Safety Monitoring System (SSMS) in NCREE.*

Conclusions

High seismicity is an imperative issue in Taiwan. Inescapable earthquake disasters can be mitigated by the development of disaster prevention technologies in earthquake engineering. Three examples conducted by NCREE after the 1999 Chi-Chi earthquake are presented in this paper. The first one is to clarify how large the seismic threat by a novel PSHA procedure. Then, the seismic performance of school buildings was comprehensively improved by seismic evaluation and retrofitting to protect students and teachers. Finally, the advanced earthquake early warning system and structural safety monitoring system that can help reduce the loss of life and property when major earthquakes occur was introduced.

NCREE is committed to lead improving applications of earthquake engineering. Plenty of researches have been completed for earthquake disaster mitigation. Furthermore, the new Tainan Laboratory, completed in 2017, and the new addition of research space in the Taipei research building, completed in 2020, has further strengthened the research resource of NCREE. We will keep moving forward with the seismic safety of Taiwan.

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