Survey Report:

Citizen Earthquake Science in Taiwan: From Science to Hazard Mitigation

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Taiwan is located at the convergent plate boundary between the Eurasian and the Philippine Sea plates. As a result, intense earthquake activity and associated surface deformation are manifesting in this region. To implement and promote citizen earthquake science in Taiwan, we have developed several web-based platforms with multi-purpose themes, such as earthquake science information, popular science education, and crowdsourcing systems. First, with the rapid earthquake report issued from the Taiwan Central Weather Bureau (CWB), the available near real-time scientific results obtained from the Taiwanese seismology community are collected and published to a platform, the Taiwan Earthquake Science Information System (TESIS). The scientific information archived at TESIS includes CWB earthquake reports, focal mechanisms, shake maps, and finite source models (for strong earthquakes). All real-time results are integrated into a GIS system with background geospatial information, such as geological maps, traces of active faults, background seismicity, and inter-seismic GPS velocity fields. Second, by collaborating with Stanford University to maintain a regional Quake-Catcher Network (QCN) server in Taiwan, we have promoted citizen seismology in Asia by bringing earthquake information and scientific knowledge to the public. More than 200 school teachers have already installed the QCN sensors in Internet-enabled computers. Through two web-based educational platforms, users are able to access the guidelines and further interact with the recorded waveforms. Third, we also developed an earthquake damage reporting system – the Taiwan Scientific Earthquake Reporting (TSER) system – to encourage the citizen to collect field observation for significant earthquake-induced ground damages such as surface fault rupture, landslide, rock fall, liquefaction, and landslide-triggered dam or lake. The TSER system is constructed under the Ushahidi mapping platform, which has been widely used in crowdsourcing for the geospatial archiving of events. Trained high school teachers and public volunteers can send their ground damage observations, including photographs, through the TSER system. Most of these products and online systems are now being operated by the Taiwan Earthquake Research Center (TEC). With these newly developed platforms and materials, we aim to not only raise earthquake awareness and preparedness, but also encourage public participation in earthquake science in Taiwan.

Keywords: citizen earthquake science, crowdsourcing, Taiwan Earthquake Science Information System (TESIS), earthquake school in the cloud, Taiwan

1. Introduction

Located at a convergent plate boundary zone between the Eurasian plate and the Philippine Sea plate, Taiwan is an earthquake-prone region in the western Pacific margin. **Fig. 1** shows earthquake activity of $M_L \geq 5$ that has occurred in the past 25 years, together with their focal depths. There were approximately 30 events of $M_L \geq 5$ every year around the Taiwan region. Taking the disastrous 1999 M_w7.6 Chi-Chi, Taiwan Earthquake as an example, although the Taiwan Central Weather Bureau (CWB) successfully issued a rapid earthquake alarm of M_L7.3 102 seconds after the earthquake [1], the instrumental seismological parameters had not yet been connected with other background geospatial information on a real-time basis. Moreover, because the electricity and communication infrastructures were severely damaged, the scientists at the beginning, struggled to identify the corresponding active fault. Despite the well-known seismic risk in the highly populated area of western Taiwan, the public generally lacked knowledge of seismic hazard preparedness and mitigation. After the 1999 Chi-Chi Earthquake, the Taiwan government began to pay attention to the need for preparedness by requiring regular earthquake drill in schools and governmental departments. Meanwhile, as proposed by Kanamori [2], people have started to understand that real-time seismology is critical to earthquake damage mitigation. In 2001, the CWB launched an earthquake early warning (EEW) system [3]. Now, the current response time to issue an earthquake alert is less than 20 seconds, with hopes to shorten it into 10 seconds in the

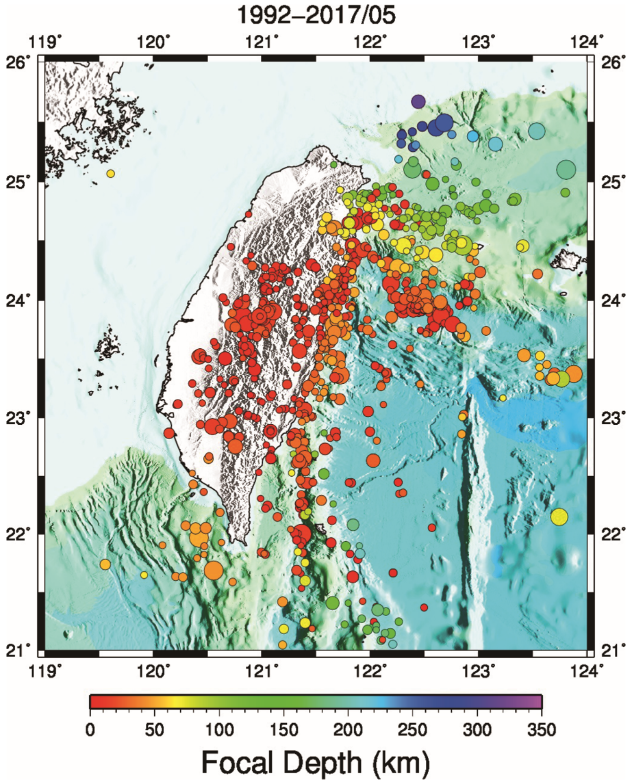

Fig. 1. Taiwan $M_L \geq 5$ earthquakes in the past 25 years.

near future to provide more warning time [3]. In addition to the regional EEW system, an on-site warning system equipped with low-cost sensors (P-Alert) was also developed in Taiwan [4]. Its performance proved to be good during the 2016 M_w6.3 Meinong Earthquake [5] in the vicinity of Tainan City.

In addition to quick reporting of the earthquake location and magnitude issued by CWB, the earth science community of Taiwan built a real-time moment tensor monitoring system (RMT) to simultaneously determine the focal mechanism and other source parameters of earthquakes [6]. This RMT system takes advantage of a grid-based moment tensor inversion technique and real-time seismic recordings from the Broadband Array in Taiwan for Seismology (BATS) [7], operated by the Institute of Earth Sciences (IES), Academia Sinica. To assess the seismic hazard and risk in Taiwan, the Taiwan Earthquake Model (TEM) project published its first probabilistic seismic hazard analysis (PSHA) results in 2015 [8]. By combining population and facility distribution maps, additional exposure analyses are under investigation based on these PSHA maps [8, 9]. This system aims to provide a quantitative assessment of earthquake casualties and damages using a scientific method.

It remains challenging to communicate scientific information and the achieved seismological technologies to the public and industry. Based on the experiences of the 1999 Chi-Chi earthquake and subsequent seismological technologies, this project intends to (1) construct a web-based platform to integrate all available real-time earthquake science information and background geospatial data, (2) promote earthquake science in a cloud-based platform, (3) implement a crowdsourced eyewitness and reporting system for gathering detailed ground observations during earthquakes, and (4) encourage citizen participation in science. The ultimate goals are to enhance the public awareness of earthquake hazards and to promote citizen seismology in Taiwan.

2. Taiwan Earthquake Science Information System (TESIS)

Accurate and timely scientific information for an unexpected large earthquake can provide assistance in at least three general ways: (1) assisting government, decision-makers, and emergency agencies in immediately and precisely locating damage zones or areas, (2) assisting the public in evacuation and preventing them from entering into damage zones, and (3) assisting scientists in better understanding earthquake scientific parameters and corresponding geological structures.

2.1. Ingredients of TESIS

The TESIS platform is an online, automated, and near real-time information/data integration system [10]. It collects all available scientific results from various research institutions for felt earthquakes in the Taiwan region for which the CWB issued alerts. These results include focal mechanisms determined by inverting the BATS waveforms [e.g., 6, 7], intensity maps offered by CWB and the P-Alert group of the National Taiwan University (NTU) [4], and co-seismic deformation revealed by surface GPS measurements and determined by the GPS Lab in Academia Sinica. To archive these diverse results, we negotiated with various organizations to define their web locations and data formats. For the real-time P-Alert intensity, we adopted the Earthworm seismic data acquisition system [11] to receive the shared continuous P-Alert data streams to compute the real-time ground shaking during and after an earthquake. This research-based intensity information is accessible online via website [12] and social media [13]. We implement several algorithms to invert the BATS waveforms for obtaining robust moment magnitude and focal mechanisms. When those solutions are consistent with each other, it may imply that the earthquake focal mechanism is well determined. **Fig. 2** presents the major components of the data/information and their sources integrated in TESIS.

2.2. Division of Tectonic Domains

Due to the complex tectonic plate configuration in the Taiwan region, the heterogeneity of seismogenic structures can be expected. According to previous work, we have summarized the whole region into 20 active subdomains as shown in **Fig. 3**. The 20th domain, which is not shown in **Fig. 3**, is the area at the intermediate depth where earthquakes are associated with two subduction systems to the northeast and to the south of Taiwan. Once

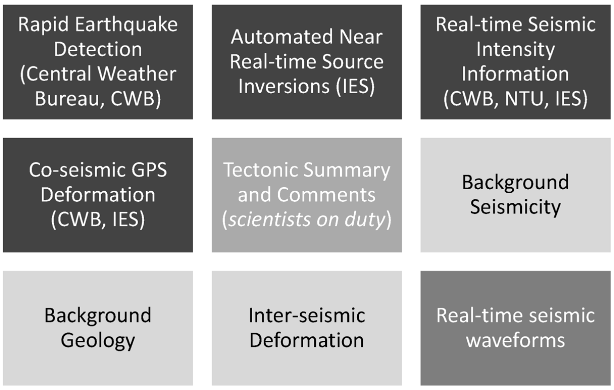

Fig. 2. Data contents and their sources in the TESIS platform.

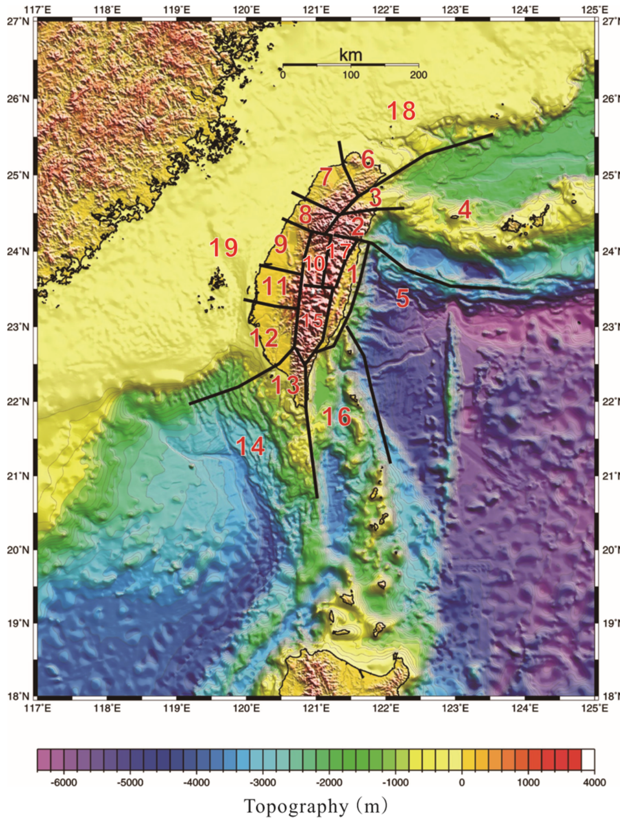

Fig. 3. Division of tectonic domains in the Taiwan region.

Fig. 4. Portal page of TESIS at http://tesis.earth.sinica.edu.tw.

Fig. 5. Scientific information content for the 2016 M_w6.3 Meinong Earthquake.

a significant earthquake occurs, the corresponding domain descriptions of the background tectonic setting will be automatically posted in the web page of TESIS according to the hypocenter location determined by CWB. The scientist(s) on duty will summarize all available real-time scientific information and provide comments on the earthquake's characteristics, its relationships with regional tectonics and geology, seismogenic structure, seismic hazard, etc.

2.3. Functions of TESIS

Figure 4 shows the portal page of TESIS, in which 3 major items – (1) archived events, (2) latest events and (3) Taiwan earthquake facts – are presented from left to right. When a user clicks on any event in the middle panel, the associated scientific information as summarized in **Fig. 2** will be shown as in **Fig. 5**[1]. This example shows the results for the 2016 M_w6.3 Meinong earthquake, which caused severe damage in southwestern Taiwan. This platform provides the community the most complete integrated scientific information. Many constructive comments and numerous exchanges among scientists benefit from TESIS during the first few days following an earthquake. The left panel lists information options to be superimposed in the embedded Google Map. In this case, the gCAP [14] focal mechanism, P-Alert intensity and active faults were selected to be embedded. Obviously, the largest intensity is located to the NW of the epicenter, which is believed to be related to the composite effects of site amplification and the rupture directivity [5, 15]. Several focal mechanisms results obtained from different inversion algorithms based on BATS and shared regional waveforms were collected for comparison. All solutions are consistent with each other, implying a reliable determination of focal mechanism.

Once TESIS receives the hypocenter report from CWB, the corresponding background tectonic description will

1. http://tesis.earth.sinica.edu.tw/showDetail.php?date=%222016-02-06%22&time=%2203:57:27%22

appear beside the map. In addition, users are able to select other information to be shown on the map, including the background seismicity, geological map, interseismic deformation, and coseismic deformation (if a large event). The left panel in **Fig. 4** is for an archived earthquake catalog. Historic events from April 2010 can be found from this interface. Some basic earthquake knowledge, as well as tutorial material, is compiled in the right panel, which is especially useful for instructors and students.

With this integrated information system, scientists can not only more easily identify the associated seismogenic structure (or geological fault), but also assess seismic hazards and understand what other geohazards, such as liquefaction and landslides, may be triggered during the earthquake. Additionally, the general public is able to obtain up-to-date scientific information from TESIS instead of relying on rumors from unreliable sources, which could cause misunderstandings.

3. Crowdsourcing Systems

To encourage public participation in gathering earthquake information, we have constructed 2 crowdsourcing-based online systems to collect citizen responses to earthquakes. The first one is the Taiwanese version of the "Did You Feel It? (DYFI)" program running in USGS [16, 17, 18], which converts qualitative descriptions into relevant intensity through online questionnaires. The second aims to collect field observations on any earthquake-induced natural geohazards, such as surface ruptures, landslides, liquefaction, and landslide-triggered dams or lakes, by trained volunteers after the occurrence of a significant earthquake.

3.1. Did You Feel It? (DYFI@Taiwan)

The DYFI program operated by USGS has achieved great success in obtaining a Community Internet Intensity Map (CIIM) in the US [17, 18]. In many other regions, online questionnaires are also widely applied to collect this kind of internet intensity [e.g., 19]. We basically follow a similar strategy to establish a Taiwan version of the DYFI system [20]. To obtain detailed intensity information from personal experience, we first designed a few questionnaires based on the qualitative descriptions of the CWB intensity scale, ranging from 0 to 7. Then, we defined a series of weighted functions for all of the answers to calculate a body-sensed intensity at the response location. For instance, a volunteer reports (1) a felt earthquake and (2) was a bit frightened, but (3) the furniture was not moving at all, and the corresponding intensity functions are ≥ 1, ≥ 3 and ≤ 4, respectively. In this case, the body-sensed intensity would be calculated as 3.5. After running this DYFI system in Taiwan for one year, we found some major challenges:

- Too many questions prevent volunteers to finish the questionnaires.

Fig. 6. An example of crowdsourced intensity for the 2016/05/31 Mw 6.4 event at DYFI@Taiwan. The shake map in colors is derived from P-Alert observations[2].

- Subjective description biases the estimated internet intensity.
- Lack of feedback lowers the number of citizen responses.

To overcome these problems, we reduced the number of questions from 15 to 5, in order to have concise Internet intensity mapping and enhance the number of citizen responses. It is unavoidable that citizen responses are very subjective, and thus the success of the program depends on a large number of online replies. This issue may be addressed if we better promote the DYFI@Taiwan system to the public. We are seeking efficient ways to promote this online questionnaire right after a significant earthquake. TESIS and social media seem to be the most powerful channels to engage people to participate in the online survey. Additionally, we are planning to add a measure of personal contributions to the CIIM and to offer a ranking board for further applications. **Fig. 6** is an example for an M_w 6.4 intermediate depth event that occurred beneath northern Taiwan in May 30, 2016. Although we received more than 100 responses from around Taiwan, the body-sensed intensity is obviously different from the results of P-Alert intensity. The concise version of the online questionnaire has just been launched in 2017 and hopefully it will provide a new and improved CIIM.

3.2. Taiwan Scientific Earthquake Reporting System (TSER)

To immediately collect field observations for any earthquake-induced ground damage, such as surface fault ruptures, landslides, rock falls, liquefaction, and landslide-triggered dams or lakes, we are developing an

2. http://tesis.earth.sinica.edu.tw/DYFI/showmap.php

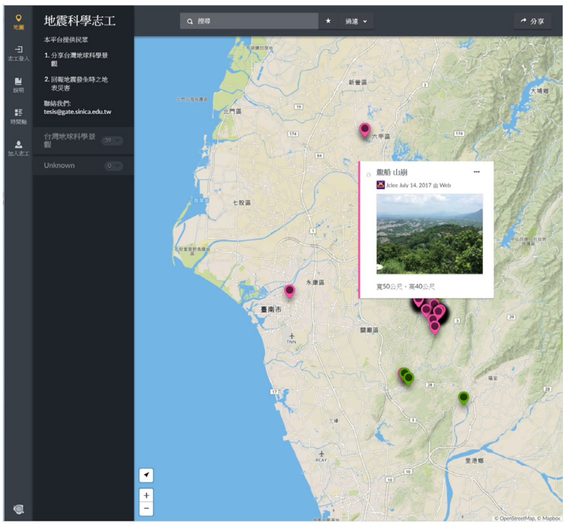

Fig. 7. The Taiwan Scientific Earthquake Reporting System based on the Ushahidi mapping platform.

earthquake damage reporting system that particularly relies on schoolteacher volunteers who have taken a series of training courses organized by this project. The topics of our training courses cover (1) overview of Taiwan tectonics and geology, (2) historic earthquakes and their impacts, (3) geohazards of Taiwan, (4) volunteer development, (5) citizen seismology, and (6) field excursions. This Taiwan Scientific Earthquake Reporting (TSER) system [21] is based on the Ushahidi mapping platform, which has been widely used for crowdsourcing for different purposes. Participants may add an app-like icon to their mobile devices to access this website [2]. Right after a potential damaging earthquake occurs in the Taiwan area, trained volunteers will be notified and dispatched to the epicenter area to carry out field surveys and to describe the ground damage through this system. If the internet is available, they may also upload relevant field images right away. This collected information will be shared with the public after a quick review by on-duty scientists. On average, Taiwan experiences one damaging inland earthquake every 2–3 years. To prepare for the next strong earthquake, we have set up a specific project on TSER for sharing spectacular and remarkable landscape or geological pictures wherever possible. This will also help volunteers become acquainted with this system and will allow volunteers to share teaching material on this platform. This experimental, scienceoriented crowdsourcing system was recently launched in mid-2017. More than 100 volunteers from different areas of Taiwan have already taken the training courses. **Fig. 7** shows the field work practice results from the 2017 training workshop.

3.3. Quake-Catcher Network (QCN-Taiwan)

The Quake-Catcher Network (QCN) is a seismic network that implements distributed/volunteer computing with the potential to provide critical earthquake information by filling in the gaps between traditional seismic stations [22]. Since 2012, we have collaborated

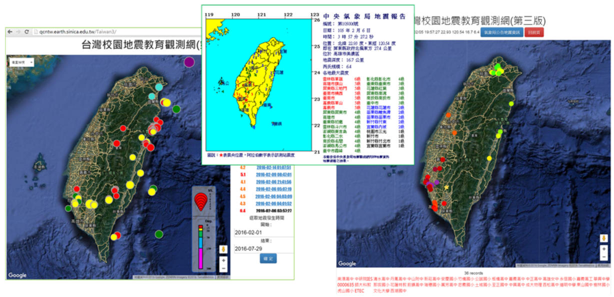

Fig. 8. Seismic intensity map from the Taiwan Quake-Catcher Network. (left) Epicenters issued by CWB, (middle) a rapid earthquake report issued by CWB, (right) shaking intensity revealed at every QCN site.

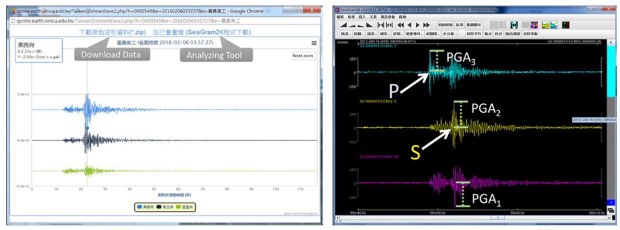

Fig. 9. (left) Event waveforms recorded at one QCN station. (right) Using the Seisgram2K software to further analyze the downloaded waveforms.

with the QCN project, initiated by Stanford University, to form an educational strong motion network in Taiwan [23]. Although the traditional seismic networks operated by CWB [3] have covered all of Taiwan, the recorded waveform data is not accessible in a real-time manner. The QCN-Taiwan project aims to enable teachers and students to become acquainted with waveform data recorded at their schools. Teachers may request micro-electromechanical systems (MEMS) sensors from our project to allow any Internet-enabled computers with a MEMS accelerometer to act as a strong motion seismic station. Event data are automatically extracted from the QCN-Taiwan network [24] when the CWB earthquake alert is issued. **Fig. 8** shows an online interface for accessing the QCN event-based waveform data. Users can click on QCN stations to view the recorded waveform or to download the SAC [25] format data for further analysis using SeisGram2K [26] or other software products. In **Fig. 9**, the arrival times of both P and S waves, as well as peak ground accelerations (PGAs) observed for three component waveforms, can be easily identified from the graphic interface. With this crowdsourced dataset from distributed/volunteer computing, an educational strong motion network has been achieved in the Taiwan region.

4. Promoting Earthquake Science in Taiwan

The Taiwan Earthquake Research Center (TEC) [27] is a virtual organization that is sponsored by the Ministry of Science and Technology (MOST) of Taiwan and is now based at the IES. The missions of TEC are to (1) initiate research in new fields and to implement research outcomes in Taiwan, (2) integrate all available resources for the research community, and (3) promote earthquake science education and outreach to better prepare citizens for future earthquake impacts. TEC has closely collaborated with universities and research institutions to provide online materials for educational and outreach purposes. Below, we introduce some recent major achievements of TEC.

4.1. Earthquake School in the Cloud

The Citizen Seismologists in Taiwan project has been conducted to elevate the quality of earthquake science education by incorporating earthquake and tsunami stories and educational earthquake games into traditional school curricula. The project aims to build a cloud-based computing service incorporating an earthquake school, where teachers can easily teach their students about earthquakes and children can learn about earthquakes in a fun environment [23, 28]. In addition to the teaching resources designed in this project, a near real-time earthquake game competition has been implemented for users to learn how to determine the epicenter location, shake map, magnitude and even the first-motion focal mechanism [23, 28]. This brand new experiment has attracted many high school teachers to include this activity in their teaching curricula.

4.2. Earthquake Teachable Moments

The residents in metropolitan Taipei have many experiences of earthquake ground shaking, but some of them were frightened by a rare shallow event with M_L4.2 on Feb. 11, 2014. Although the ground shaking duration was only a few seconds, the observed PGA of 66 gals in the source region near the northern edge of the Taipei basin made residents alarmed over the sudden shock. After this event, TEC decided to form a Commission on Education and Outreach (CEO). Its main mission is to integrate all available scientific information, including real-time and rapid solution of earthquakes (mostly from TESIS), previous literature, historic events, associated seismic hazards, and interpretation of the earthquake, into a document to spread the earthquake science in a few hours after a significant earthquake occurs. The CEO will collect information not only for significant earthquakes in the Taiwan region, but also for strong and damaging earthquakes in other parts of the world if their impact is obviously foreseeable. These educational documents are available on TEC's website [27] and social media [29].

4.3. TEC E-Newsletter

TEC has regularly published a quarterly electronic newsletter to share research accomplishments, from earthquake science to hazard mitigation, by Taiwan's seismology community. This E-Newsletter covers TEC's activities, invited articles, and data and instrument announcements [30]. The target readers are high school teachers


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「地震衝擊資訊平台(TERIA)」開發與應用

國家災害防救科技中心開發適用於國內地震防災應用的網格化衝擊分析技術，並自 104 年起持續建置網路版「地震衝擊資訊平台(TERIA)」(圖一)，網址為 http://teria.ncdr.nat.gov.tw/Teria(目前僅開放地震防災應用相關人員使用)，目的在於整合地震衝擊分析相關技術與研究成果，透過研究及資訊主題之整合，提供地震災害衝擊情境評估資訊。

TERIA 運用 GIS 地理資訊系統，以 500m×500m 地理網格為單元進行模擬，有效串聯中心自行開發撰寫之地動、液化、坡地崩塌、建物、人口、道路、橋梁、供水、電力與瓦斯管線衝擊分析模組，除了具備基本資料查詢，更新增衝擊分析及分析結果查詢與展示功能，並依使用者需求建立不同主題式應用介面，以提供多元化應用的地震衝擊分析資訊。

TERIA 已完成自動化演算、匯出圖資和數值資料等功能，能夠提供災前減災策略規劃、設計演習情境與腳本之依據。目前已應用於 105 年國家防災日地震模擬情境設定(圖二)，以第七屆行政院專家諮詢委員會「全災害管理體系建構-都會型大規模地震災害為例」之議題分析情境模擬，並協助「北北基桃」聯合演練、宜蘭縣、南投縣、高雄市、屏東縣等縣市地震演練情境之分析與設定。(由國家災害防救科技中心柯孝勳博士撰寫)

圖一、地震衝擊資訊平台(TERIA)架構及其應用。

圖二、地震衝擊資訊平台應用於 105 年國家防災日地震模擬情境設定。

Fig. 10. Latest (June, 2017) TEC Newsletter.

and freshman students. **Fig. 10** is an article, which introduces the development of the Taiwan Earthquake Impact Research and Information Application (TERIA) platform by the National Science and Technology Center for Disaster Reduction (NCDR), that was published in the latest newsletter (June 2017)[3].

4.4. Online Classroom Activities

Some have suggested that games on disaster reduction education are more beneficial than other approaches [30]. We have designed an interactive facility – the Near Real-Time Earthquake Game Competition [31] – as an educational tool that creates a fun environment for learning basic earthquake science in the classroom. With basic knowledge of how to read seismograms and what to look for in the data, students can interact with the waveforms to (1) locate the earthquake epicenter (picking P and S first arrivals), (2) measure the seismic intensity and magnitude (picking maximum amplitude), and (3) determine the fault plane solution (picking initial P-wave motion polarities) [31]. Background knowledge is introduced during the games through pop-up guides. The corresponding teaching resources that supplement the practice earthquake games with informative stories can be found online [28].

5. Summary

In the past five years, we have developed a web-based Taiwan Earthquake Science Information System (TESIS), three crowdsourcing platforms, and a series of educational tools for teachers, students, and the general public to implement and promote citizen seismology in Taiwan. Our

3. This article can be found at http://tec.earth.sinica.edu.tw/new_web/upload/publications/TEC-Newsletter_201706.pdf

Table 1. Summary of system/work developers and operators.

Systems/Applications	***Developer(s)***	***Operator***
TESIS, Taiwan Earthquake Scientific Information System	IES, CWB	TEC
DYFI@Taiwan	IES	TEC
TSER, Taiwan Scientific Earthquake Reporting System	IES	IES
QCN-Taiwan	IES	TEC
Earthquake School in the Cloud	NTNU, IES	NTNU
Teachable Moment	TEC	TEC
e-Newsletter	TEC	TEC
Online Classroom Activity	IES	TEC

IES: Institute of Earth Sciences, Academia Sinica
CWB: Central Weather Bureau
TEC: Taiwan Earthquake Research Center
NTNU: National Taiwan Normal University

intention is to make the developed facilities work together as a framework to promote public involvement in earthquake science and hazard mitigation. The institutions that develop and/or operate the systems and applications described in this article are summarized in **Table 1**.

Acknowledgements

We would like to thank the office of the Taiwan Earthquake Research Center (TEC) for maintaining these developed systems and applications under the leadership of Prof. Kuo-Fong Ma. This work was supported in part by the "Open Information System for Disaster Management, OpenISDM" and "Disaster Resiliency through Big Open Data and Smart Things, DRBoast" projects (Funding agency: Center for Sustainability Science, Academia Sinica), as well as the Taiwan Earthquake Research Center program (TEC) (Grant Numbers: MOST 106-2119-M-001-021 and 105-2119-M-001-034; TEC Contribution Number for this article is 00139.) (Funding agency: Taiwan Ministry of Science and Technology, MOST).

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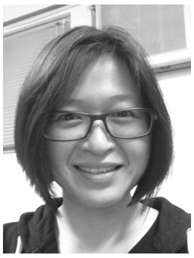

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