EDUQUAKES

Earthquake School in the Cloud: Citizen Seismologists in Taiwan

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ABSTRACT

It is hoped that through the cultivation of a crew of volunteer citizen seismologists, public involvement could be encouraged and the discovery and inquiry into earthquake knowledge could be promoted. These volunteers can contribute to data collection, analysis, and reporting, and have the potential to greatly improve the emergency response to earthquakes. The Citizen Seismologists in Taiwan Project (CSTaiwan) is designed 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 (i.e., a website for online learning) where teachers can easily teach their students about earthquakes and children can learn about earthquakes in a fun environment. Here we demonstrate how students perform *P*- and *S*-wave picking and measure seismic intensity through an interactive learning platform, how scientists and school teachers work together, and how we create a near-real-time earthquake games competition to facilitate continuous learning while making earthquake science fun. We also develop 49 questions associated with participants' preknowledge, attitude, and skills in earthquake sciences, called Citizen Seismological Literacy (CSL). The CSL model may serve as an example to quantify citizen's background in earthquake sciences and could be applied as a framework for seismologists around the world who wish to approach the public for educational purposes, while considering promoting the public's seismologic literacy.

INTRODUCTION

To better prepare citizens for future impacts of natural disasters, it is important to understand how previous disasters have occurred, why lives were taken, and what lessons have been learned. Such understanding allows the attitude of the public to change from training to learning for natural disaster preparedness. Taiwan is one of the most vulnerable places on Earth for natural hazards, with 73% of its land area and population exposed to more than three types of natural hazards (Dilley, 2005). Unlike floods, landslides, and cyclones, earthquakes only afford a short period of time for reaction and response (e.g., usually less than 10 s). It is therefore crucial to increase the capability and knowledge of the Taiwanese citizens regarding earthquake science, specifically as to why earthquakes happen, how they occur, and how we should best prepare ourselves and the city for an earthquake hazard.

It is hoped that through the cultivation of a crew of volunteer citizen seismologists, public involvement could be encouraged and the discovery and inquiry into earthquake knowledge could be promoted. These volunteers can contribute to data collection, analysis, and reporting, and have the potential to greatly improve the emergency response to earthquakes. The Citizen Seismologists in Taiwan Project (CSTaiwan) is designed 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 (i.e., a website for online learning) where teachers can easily teach their students about earthquakes and children can learn about earthquakes in a fun environment.

Through a pilot program of courses and professional development workshops, we worked closely with teachers in elementary, junior high, and senior high schools to design workable teaching plans incorporating the practical operation of seismic monitoring at homes and schools. As well as providing an update on the citizen seismic networks in Taiwan, this article demonstrates how students perform *P*- and *S*-wave picking and measure seismic intensity through an interactive learning platform, how scientists and school teachers work together, and how we create an environment to facilitate continuous learning (via a near-real-time earthquake games competition) while making earthquake science fun.

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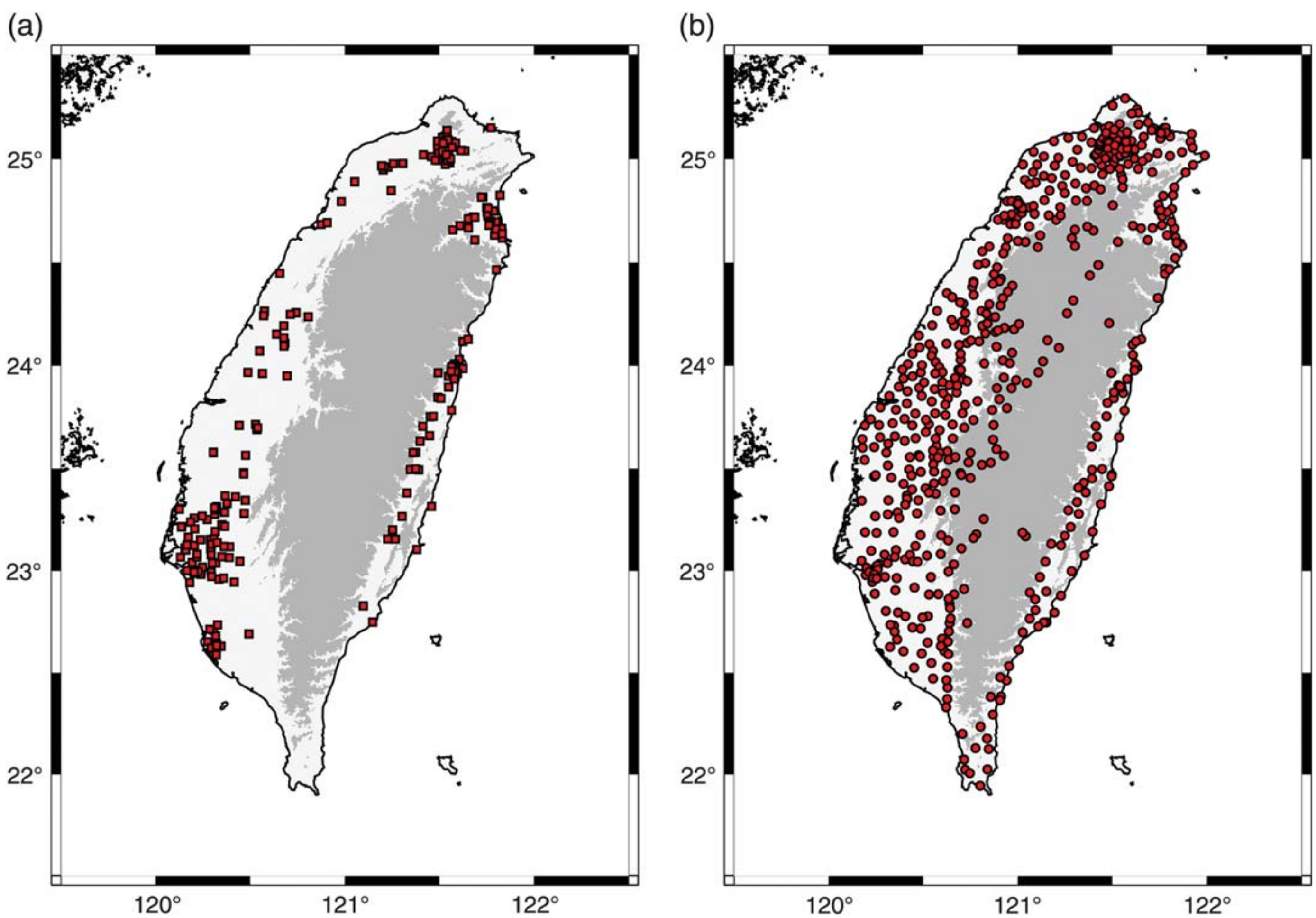
CITIZEN SEISMIC NETWORKS IN TAIWAN

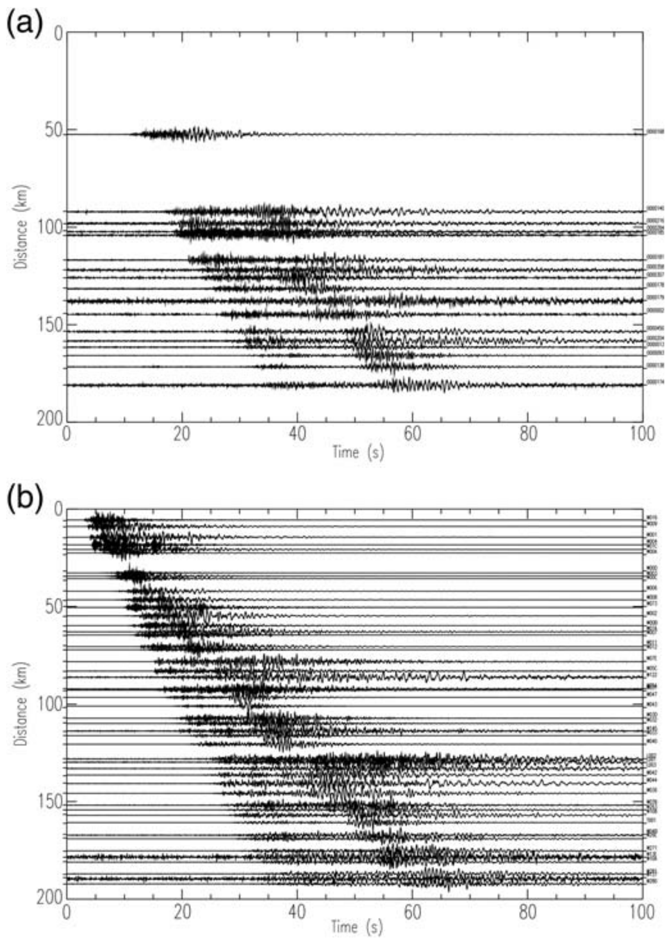
We have been collaborating with Stanford University to maintain a regional Quake-Catcher Network (QCN) server in Taiwan (Cochran *et al.*, 2009) for promoting citizen seismology in Asia. Over the past two years, more than 170 volunteers in schools requested sensors and installed these sensors in Internet-enabled computers. System logs indicate that the sensors are, on average, active 50%–60% of the time. This data set has been used for reporting seismic intensity and online waveform analysis. Figure 1a shows the current QCN site distribution in Taiwan, mainly covering the highly populated areas. To increase the spatial resolution of sensor data, we also implemented an online interface to receive real-time data from the existing *P*-alert strong-motion network (Wu *et al.*, 2013), which features up to 543 stations (Fig. 1b) and availability of $>80\%$. Figure 2 demonstrates the improvements in *P*-alert data coverage at various epicentral distances. The *P*-alert network is composed of low-cost microelectromechanical system (MEMS) accelerometers, which are embedded with real-time seismological algorithms to provide on-site earthquake early warning (EEW, Wu *et al.*, 2013), as well as near-real-time ground-motion intensity measurements. Because of the success of the online EEW system (*P*-alert), both the Minister of Education and the Minister of Science and Technology have attempted to promote this island-wide school network.

The *P*-alert signal resolution is 16 bits with a $-2g$ to $+2g$ range, and the sampling rate is 100 samples per second. The full-scale range of QCN MEMS sensors is also $\pm 2g$, but most of them are of 12-bit resolution. Only few 16-bit sensors were given to volunteers who are located in relatively higher seismicity area. The sampling rate of the QCN waveform is 50 samples per second. In addition to the differences in sensor specification and embedded seismological algorithms, QCN sensors were all hosted by school volunteers, whereas the *P*-alert devices were installed mainly in schools and maintained by technicians of the *P*-alert team.

The recorded waveforms for QCN and *P*-alert for the 31 October 2013 M_w 6.3 Ruisui earthquake that occurred in Hualien, Taiwan, are shown in Figure 2. It is obvious that the quantity of recorded *P*-alert waveforms is much higher than those recorded by QCN-Taiwan, but the combined QCN and *P*-alert citizen seismic networks can provide dense station coverage and a high-resolution seismic intensity map. Continuous



▲ **Figure 1.** (a) Quake-Catcher Network (QCN) and (b) *P*-alert citizen seismic networks in Taiwan. Gray color represents mountainous area with elevation higher than 500 m. The color version of this figure is available only in the electronic edition.



▲ **Figure 2.** Waveforms recorded by (a) QCN-Taiwan network and (b) *P*-alert network for the 31 October 2013 M_w 6.3 Ruisui earthquake that occurred in Hualien, Taiwan. Only one trace is plotted within each 4 km distance interval to allow the *P*-alert waveforms to be viewed clearly.

signals collected at volunteer homes and schools are streamed to Academia Sinica in Taiwan for data archiving.

However, there is often a demand for seismic data access and education from the volunteers, in particular the high school teachers. Because of this demand, we aim to not only encourage volunteers to install novel cheap sensors (~$70 U.S.) at homes and schools, but also to make the recorded seismic data useful in classrooms. To begin with, we developed teaching materials that enable citizens to learn the information hidden in seismograms: for example, where and how big the earthquake is and what type of faulting occurred. These teaching materials are engaged in a near-real-time earthquake games competition. Below we will introduce the teaching resources and games in the Teaching Resources and Near-Real-Time Earthquake Game Competition sections, respectively.

TEACHING RESOURCES

To help volunteers understand the basic seismology and physics, we developed teaching materials that enable citizens to learn through a YouTube video clip (1–6 min long) or to enable teachers to teach it in their classrooms. We prepared six teachable units that closely tie in informative stories with the practice earthquake games (see the Near-Real-Time Earthquake Game Competition section). Units consist of the following: (1) "Orphan Tsunami" (a story), (2) Finding Earthquakes (a game), (3) "The 2004 Sumatra Earthquake and Tsunami" (a story), (4) Sizing Up Earthquakes (a game), (5) "Forensic Seismology" (a story), and (6) Making Fault Motions (a game). The learner can watch the YouTube video for pre-education purpose. In our pilot, each unit takes about 30 min to introduce the important concept.

Each story has an associated game unit. Unit 1 (Orphan Tsunami) describes the real tsunami event that occurred on 26 January 1700 (Atwater *et al.*, 2005). This mysterious tsunami arrived at Japan along the coastline from north to south over a distance of 1000 km, leading to flooded fields, wrecked houses, fire, shipwreck, evacuation, and panic. However, no earthquake was felt in Japan. The 1700 tsunami remained an orphan for ~300 years. In the 1980s, geologists found the remains of sunken marshes and forests as evidence of a "parent" earthquake in North America, in an area that was not known to have experienced an earthquake greater than M_w 7.5 in recorded times. This unit teaches (1) why a subduction zone earthquake is dangerous; (2) under which conditions, following the earthquake, the devastating tsunami was initiated; and (3) how to find evidence of past earthquake and tsunami events. In the modern world, however, earthquakes can be found by reading seismograms. This leads to unit 2, in which students participate in an earthquake game called Finding Earthquakes. By picking *P*- and *S*-wave arrivals at more than three stations, the students are able to locate an earthquake. The teaching material and practical application teaches (1) what *P*, *S*, and surface waves are; (2) how to pick *P* and *S* waves; and (3) how to use the time difference between *P* and *S* arrivals to determine the earthquake location.

Unit 3 describes the Sumatra earthquake and tsunami. In 2004, an M_w 9.3 earthquake occurred in northern Sumatra, the biggest event since the 1960 M_w 9.5 Chile earthquake. The rupture propagated northward with a speed of ~2 km/s, covering 400 km within 200 s. On the surface, the strong shaking lasted 8 min. Fifteen minutes following the earthquake, a tsunami hit Aceh and caused ~100,000 deaths, at a location where people were not prepared for a disastrous tsunami. The Pacific Tsunami Warning Center did, in fact, issue a warning tsunami bulletin 15 min after the occurrence of the earthquake; however, the warning claimed that "no destructive tsunami threat exists" due to the underestimation of the earthquake magnitude as M_w 8.0. Therefore, the quick and precise determination of earthquake magnitude is key to detecting tsunamis in advance and to having the ability to issue warnings to prevent loss of life. This unit teaches (1) what the precursory signals before a massive tsunami are; (2) how the amplitude of the seismic signal correlates with earthquake magnitude; and (3) what information is required for effective tsunami warning. This leads to unit 4, the Sizing Up Earthquakes game, in which students can measure the magnitude

▲ **Figure 3.** The front page of the near-real-time earthquake games competition website. Each animal represents a different game. Once the certificate is achieved, the user can enter the competition platform (indicated by the flower) to contribute to real earthquake information. The color version of this figure is available only in the electronic edition.

of an earthquake by picking the maximum amplitude on three-component seismograms.

Unit 5 (Forensic Seismology) aims to show how a seismologist acts as a forensic scientist to detect secret nuclear test explosions, mine collapses, and submarine explosions. This unit teaches (1) historical ground-shaking events that require seismologists to find the source and (2) seismic discrimination between earthquakes and explosions/implosions. One of the seismic signatures that clearly shows the distinction between an earthquake and an explosion is the focal mechanism, which describes which type of earth movement produces the earthquake. It refers to the orientation of the fault plane that slipped and is also called the fault-plane solution. This is introduced in the following unit 6, the Making Fault Motions game. By picking the initial motion polarities of the first arrival of the *P* wave, the fault type (normal, thrust, or strike slip) can be determined.

NEAR-REAL-TIME EARTHQUAKE GAME COMPETITION

We also developed a near-real-time earthquake game competition for all registered citizen seismologists in Taiwan to engage the learner in earthquake sciences by playing with real seismic data. Volunteers are encouraged to install the QCN sensor at home or school and to register as a citizen seismologist. The competition platform allows citizen seismologists to report earthquake information by processing *P*- and *S*-wave arrivals (the Finding Earthquakes game), peak ground motion (Measuring Earthquake Shaking and Sizing Up Earthquakes games), and first motion of *P* waves (Measuring How a Fault Moves game) after 10 min of an earthquake event. The front page of the platform is shown in Figure 3. Citizen seismologists here are required to complete the above-mentioned four levels of CSTaiwan certificates: (1) Finding the Earthquake requires the user to locate the epicenter of the earthquake by picking *P*- and *S*-wave arrivals at more than three stations (Fig. 4a); (2) Measuring Earthquake Shaking requires the user to measure peak ground motion by picking the maximum amplitude in three components of seismograms (Fig. 4b); (3) Sizing Up Earthquake allows the user to measure the earthquake magnitude by picking the maximum amplitude in the horizontal component with the previously defined epicenter (Fig. 5a); and (4) Measuring How a Fault Moves teaches the user to determine the the fault type (normal, thrust, or strike slip) by picking initial motion polarities of *P*-wave first arrival (up or down) (Fig. 5b). Once the four certificates are achieved, citizen seismologists can challenge themselves by taking part in the near-real-time competition, where the same data-processing skills are required.

The methods applied in the four games are detailed below.

Finding the Earthquake Game

Because velocity is equal to distance divided by time, we can determine travel distance for *P* and *S* waves by

$$L = V_P \times T_P \tag{1}$$

and

$$L = V_S \times T_S, \tag{2}$$

in which L is travel distance, V_P and V_S are velocity for *P* and *S* waves, and T_P and T_S are travel time for *P* and *S* waves. Combining the above two equations, we can then determine travel distance using the time difference between *S*- and *P*-wave travel time:

$$L = (T_S - T_P) \times V_P \times V_S/(V_P - V_S). \tag{3}$$

Using a collection of $M \geq 4$ earthquakes in Taiwan, the linear relationship between L and $(T_S - T_P)$ was obtained (Fig. 6). The slope $V_P \times V_S/(V_P - V_S)$ represents the velocity parameter used in the game. Once the *P* and *S* arrivals are picked in one station (three components of seismograms), a circle is automatically drawn with a radius equal to L and centroid equal to the location of the station. The user can process other stations and choose the point where the circles intersect.

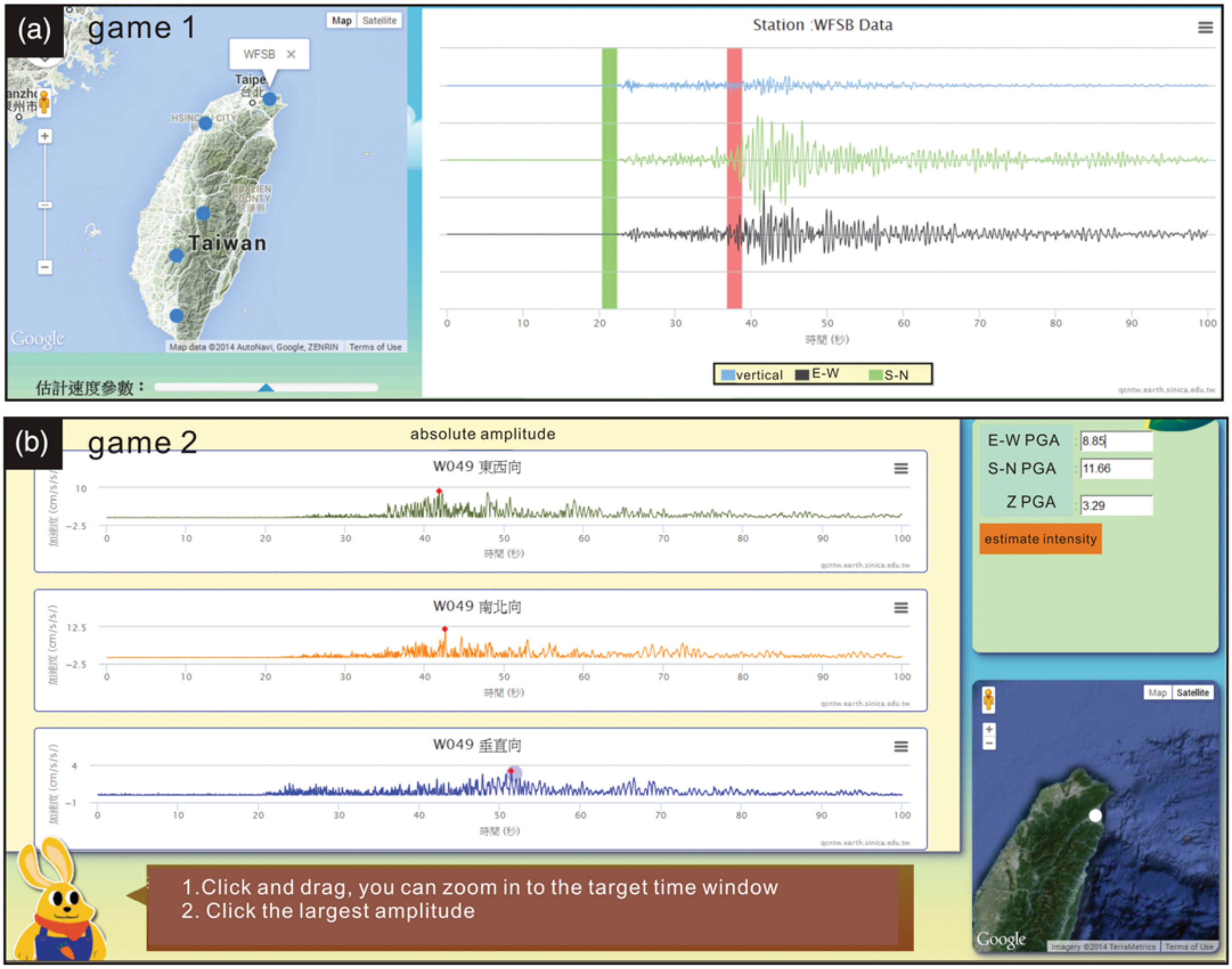
Measuring Earthquake Shaking and Sizing Up Earthquakes Games

The peak ground acceleration (PGA) in three components of seismograms is determined by picking the maximum amplitude. The empirical relationship between earthquake magnitude (M_w), travel distance (R), and horizontal PGA (hPGA) by Liu and Tsai (2005) is then applied to obtain earthquake magnitude:

$$\ln(\mathrm{hPGA}) = -0.852 \times \ln(R + 1.24) - 0.0071 \times R + 1.027 \times M_w + 1.062. \tag{4}$$

We then convert the M_w into M_L with another empirical relationship published earlier by Chen *et al.* (2009):

$$M_L = 0.8M_w + 1.264. \tag{5}$$



▲ **Figure 4.** Waveform example for the four CSTaiwan certificates: (a) Finding earthquake by picking the first arrival of *P* and *S* waves. (b) Measuring earthquake shaking by clicking the largest amplitude in three components of seismograms. The color version of this figure is available only in the electronic edition.

Measuring How a Fault Moves Game

By picking initial motion polarities of the *P*-wave first arrival, each station's location relative to the hypocenter (assuming a focal depth of 10 km) is projected onto the circular diagram with filled and open circles representing the first motion of up or down. The lower hemisphere projection is automatically produced for the user to compare with the sketch of fault-plane solutions. By the distribution of filled and open circles in Figure 7a, the user can choose the best guest from the four solutions (normal, thrust, left-lateral, and right-lateral faulting) in Figure 7b.

Scoring the Games in the Earthquake Competition

Within 10 min of an M 4 earthquake in Taiwan, the near-real-time waveform data from citizen seismic networks are released, and the competition begins. The citizen seismologists have three days to play with the real seismograms and compete with each other regarding the precision of the location of the epicenter, magnitude, and fault-plane solution. The score in the game units is determined using the algorithms listed below:

1. *Score for Finding Earthquakes game:* ($5 \le \text{Score\_1} \le 20$)
   X = Epicenter difference = (location determined by the user) – (location announced by Central Weather Bureau)

$$\textbf{Score\_1} = -0.6X + 20 \quad \text{if } X < 25 \text{ km};$$

$$\textbf{Score\_1} = 5, \quad \text{if } X \ge 25 \text{ km}.$$

2. *Score for Measuring Earthquake Shaking game:* ($5 \le \text{Score\_2} \le 20$)
   PGA difference X_i = (PGA determined by the user) – (PGA measured by the densest *P*-alert seismic network)

$$\textbf{Score\_2} = -0.2(\Sigma X_i/n) + 20 \quad \text{if } (\Sigma X_i/n) < 75;$$

$$\textbf{Score\_2} = 5, \quad \text{if } (\Sigma X_i/n) \ge 75$$

in which n is the number of stations processed.

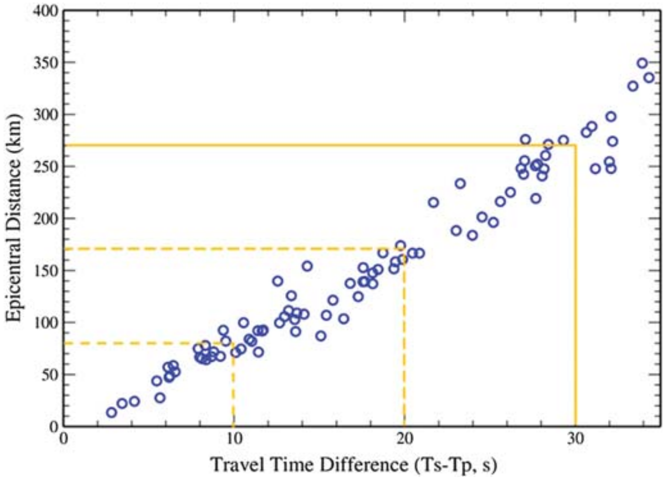
▲ **Figure 5.** Waveform example for the four CSTaiwan certificates: (a) Sizing up an earthquake by clicking the largest amplitude in the horizontal component of a seismogram. (b) Measuring how a fault moves by deciding whether the first *P*-wave motion is up or down. The color version of this figure is available only in the electronic edition.

3. *Score for Sizing Up Earthquakes game:* ($5 \le$ Score_3 ≤ 20)
Magnitude difference X = (magnitude determined by the user) − (magnitude announced by Central Weather Bureau)

$$\textbf{Score\_3} = -10X + 20 \quad \text{if } X < 1.5;$$

$$\textbf{Score\_3} = 5, \quad \text{if } X \ge 1.5$$

4. *Score for Measuring How a Fault Moves game:* ($5 \le$ Score_4 ≤ 20)
Score_4 = 20 if the fault type is the same with the one announced by Real-Time Moment Tensor Monitoring System in Taiwan by Lee *et al.* (2013) (http://rmt.earth.sinica.edu.tw/, last accessed October 2015).
5. *Additional score for number of stations processed:* ($5 \le$ Score_5 ≤ 20)
X = Number of stations processed.



▲ **Figure 6.** Epicentral distance as a function of travel-time difference (*S*-wave arrival minus *P*-wave arrival) using a collection of earthquakes in Taiwan. The color version of this figure is available only in the electronic edition.

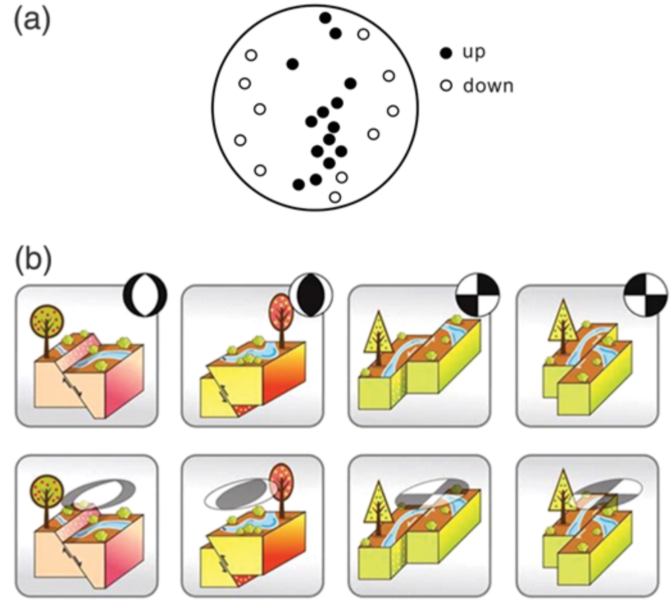
$$\textbf{Score\_3} = 0.2X + 10 \quad \text{if } X < 50;$$
$$\textbf{Score\_3} = 20, \quad \text{if } X \geq 50$$

Based on the scores, the top five players are announced and updated in real time. The users are encouraged to create their own earthquake history by saving the intensity map each time it is processed. Since September 2014 when the near-real-time competition was announced through outreach activities, the QCN volunteers increased by 45 and student volunteers increased by 163. To encourage more users to become familiar with this platform, we open guest accounts upon request. This is probably the main reason why the newly installed sensors are on average active ~50% until May 2015, almost the same compared to that prior to the release of game. The impact assessment on QCN practice/maintenance, change in knowledge, attitude, and skill in earthquake sciences will be further investigated in the near future.

OUTREACH AND CITIZEN SEISMOLOGY LITERACY (CSL)

Since May 2013, a series of third- to twelfth-grade science teacher workshops have been conducted to enhance our educational materials for the purpose of outreach. We then applied the enhanced materials in several teacher professional development workshops across the nation. With 15–80 participants in each workshop, reaching hundreds of teachers of first- to twelfth-grade education, we continually collect and analyze a variety of the participants' demographical information, preknowledge of seismology, personality self-portraits, feedback toward workshops, and other related data for potential future directions of the project.

We developed 49 questions associated with participants' preknowledge, attitude, and skills in earthquake sciences called Citizen Seismological Literacy (CSL), and their demographic information (e.g., gender, age, educator experience, etc.) and personality (i.e., personality self-portraits) were surveyed by 16 questions, as illustrated in Figure 8. Personality in the current study was studied by three subfactors: (1) conscientiousness (four questions), defined as a desire of personality to complete a task well, (2) intellect/imagination (four questions), defined as the ability to understand or depict abstract ideas (Donnellan *et al.*, 2006), and (3) grit (eight questions), defined as "perseverance and passion for long-term goals" (Duckworth *et al.*, 2007, p. 1087). In total, 65 questions were applied to study the proposed CSL model.

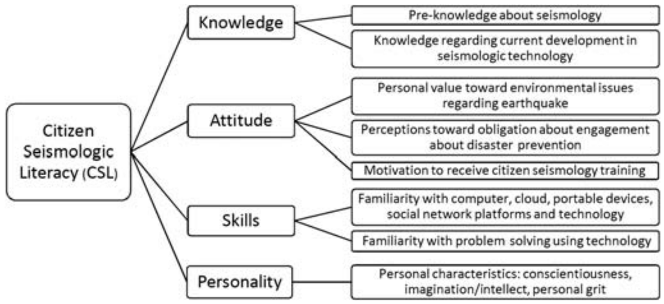


▲ **Figure 7.** Visual comparison in lower-hemisphere project between (a) the observed initial motion recorded by various seismic stations processed by the user and (b) the sketch of fault-plane solutions for normal, thrust, left-lateral, and right-lateral faulting. The color version of this figure is available only in the electronic edition.

At the present stage, however, for the purpose of having the CSL model reach the citizen, in addition to the aforementioned in-services teachers, we also tested the model within a national normal university in northern Taiwan. As a result, a total of 121 pre- and in-service teacher participants' data have been analyzed.

We assess whether personality self-portraits may have an effect on CSL (as shown in Table 1), where the asterisks indicate significant correlations. To illustrate, column 1 shows Knowledge is significantly correlated with Skill; in column 2, Attitude is significantly correlated with Skill and all Personality subfactors; in column 3, Skill is significantly correlated with all Personality subfactors; and in column 4, CSL serves as a summary of Knowledge, Attitude, and Skill (rows 1+2+3), is significantly correlated with all Personality subfactors. As a result, all three subfactors in Personality are positively related to most CSL dimensions (e.g., Attitude and Skills, but not Knowledge), providing evidence that Conscientiousness, Intellect/Imagination, and Grit have an effect on developing one's seismology literacy (CSL).

The CSL model developed in this study may serve as an example to quantify citizen's background in earthquake sci-



▲ **Figure 8.** The proposed model of Citizen Seismologic Literacy (CSL) with associated detailed dimensions.

ences. The factors controlling CSL are explored as well, which may provide a better approach to citizens' learning paths for promoting citizen seismology in the future. The proposed CSL model could be applied as a framework for seismologists around the world who wish to approach the public for educational purposes, while considering promoting the public's seismologic literacy.

CHALLENGES AND FUTURE PLAN

Primary and secondary educators were believed to be the best candidate seeders in the Taiwanese educational system because they have the potential to influence a large number of people through the student population. Thus, we particularly targeted this group and studied how they might interact and promote the idea of CSL via the QCN series workshops and further utilize the materials for teaching. However, once the participating teachers activated the QCN service, most of them failed to keep their QCN sensors operating.

We found this might be associated with the personality of the teachers (i.e., level of conscientiousness and grit), or the fact that the educational system does not facilitate educators' imagination/intellect. However, the situation may have been more complex due to the high pressure associated with the annual high school entrance test, which determines the future of 200,000 pupils every year (Yeh *et al.*, 2009; Bronson and Merryman, 2013). Teachers may also have found that supplemental teaching outside of their course materials increased their workload by an unreasonable amount. In this scenario, CSL could hardly be promoted.

Further feedback from teachers included their lack of confidence in teaching the science behind the series of QCN activities. This appeared as a common theme in our data, particularly among those teaching in elementary schools. From these results, we conclude that QCN installation and maintenance is not straightforward, observational seismology requires the skill to process the earthquake data, and there is a lack of sufficiently user-friendly, interactive tools for data sharing and networking. This represents a major challenge that the educational seismology community will need to address if operating seismographs in educational environments is to be a truly successful endeavor.

To motivate learning, users will need to have an understanding of how to read seismograms, what to look for in the data, and why their contributions are important. This can now be achieved by an interactive tool, the Near-Real-Time Earthquake Game Competition (qcntw.earth.sinica.edu.tw/games/competitionV2/, last accessed October 2015). Through a series of pilot courses and development workshops, we found that the most efficient learning happens when the audience is engaged in a competitive environment without *a priori* introduction to seismological background. In this scenario, participants often asked for supporting materials to better understand the physics behind the earthquake game. This is consistent with our CSL investigation result that background knowledge is not the most important factor. Rather, the attitude and skills of participants (highly correlated with personal grit level) are most important.

The CSTaiwan website (katepili2003.wix.com/future-eq-school, last accessed November 2015) provides the teaching resources, workshops announcements, links to access data feeds, and updated activities. Content is currently available in Chinese for Taiwanese citizens, whereas the English version of the competition game and teaching materials are still under development. In the future, we hope to collaborate with other citizen seismic networks from different countries to carry out a worldwide earthquake competition in real time.

Table 1
Pearson Correlation Matrix Regarding Citizen Seismological Literacy (CSL) Dimensions

	1	2	3	4	5	6	7
Knowledge	—						
Attitude	0.138	—					
Skills	0.233*	0.557†	—				
CSL	0.489†	0.863†	0.817†	—			
Grit	0.133	0.373†	0.345†	0.404†	—		
Conscientiousness	0.058	0.282†	0.218*	0.274†	0.409†	—	
Intellect/Imagination	0.048	0.313†	0.313†	0.329†	0.329†	0.374†	—

*Correlation is significant at the 0.05 level.
†Correlation is significant at the 0.01 level (two-tailed).

DATA AND RESOURCES

Real-time seismograms used in this study were collected by both QCN-Taiwan and *P*-alert strong-motion networks. The raid earthquake information is provided by Taiwan Central Weather Bureau (CWB, http://www.cwb.gov.tw). These waveform datasets are accessible online at http://qcntw.earth.siica.edu.tw and http://palert.earth.sinica.edu.tw/db/. All the above websites are last accessed October 2015.

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