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What We Can Learn From Japan's Early Earthquake Warning System

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Abstract
Japan's combination of high technology and cultural adaptation to its natural setting makes their earthquake detection systems a model for the rest of the world.

What We Can Learn from Japan's Earthquake Early Warning System

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I. Introduction

Japan is one of the most earthquake-prone countries in the world. The root cause of these earthquakes is the existence of hundreds of active faults embedded throughout the country as well as the continental and oceanic plates that border the country's Pacific coast. Because of this, earthquakes are a common occurrence and Japan has implemented an efficient earthquake warning system to allow residents to carry out precautionary measures. Even a 60 second warning prior to an earthquake can allow a driver to pull over to the side of the road or a student to huddle under a desk before the earthquake's ground-shaking rupture. The world saw the fatal power of natural disasters on March 11, 2011, when the 9.0 magnitude Tohoku Earthquake (東北地方太平洋沖地震） struck the east coast of Japan (US Geological Survey, 2011b). Japan's recent earthquake highlights the importance of an efficient and reliable earthquake warning system while exposing potential areas for the system's improvement. Because Japan is at the forefront of earthquake technology, this paper will analyze the strengths and weaknesses of Japan's earthquake warning system and evaluate its performance during the recent Tohoku earthquake. This paper will also discuss the cultural environment of Japan that helps to foster a successful system in order to understand how this technology can be applied to other earthquake-prone countries.

II. Overview of the Earthquake Early Warning System

Japan's Earthquake Early Warning System (EEWS; 緊急地震速報) is managed by the Japan Meteorological Agency (JMA; 気象庁), and was first launched on October 1st, 2007 (JMA, 2007b). JMA's EEWS is a type of front-detection system in which seismometers near the hypocenter, or source of the earthquake, send warnings to more distant urban areas. The EEWS is split into two phases: *earthquake detection* and *warning dissemination*. In order to determine when and where an earthquake has occurred, ground movement data is collected using Japan's dense seismic network. This information is then analyzed by monitoring stations to determine whether it is necessary to issue an earthquake warning. If a warning is justified, this earthquake information is broadcasted to nearby residents through various media such as television, radio, and cellular networks. Specialized alerts are also sent to business operators and facilities in order to deploy necessary countermeasures such as the shutdown of dangerous facilities or the slowing down of commuter trains in order to mitigate any earthquake-related damage (Scientific Earthquake Studies Advisory Committee, 2007).

Earthquake detection

For earthquake detection, it is important to understand the two types of seismic waves emitted by earthquakes: *P-waves* and *S-waves*. Although these waves are released at the same time, p-waves are less powerful and travel relatively quickly, so early recognition of these waves is critical in order to maximize warning time.

P-waves: P-waves propagate similarly to sound waves by alternating between compressing and dilating in the same direction that the wave is traveling. This longitudinal motion compresses the Earth's crust as it moves but causes very little or no destruction (Lutgens, Tasa, & Tarbuck, n.d.). These waves travel at a speed of 4-7km/second and can move through gas, liquid, and solids including the molten core of the Earth (P-Waves and S-Waves, 2009). As a result, p-waves move faster than s-waves and can be used to detect the onset of an earthquake before the arrival of the more destructive s-waves.

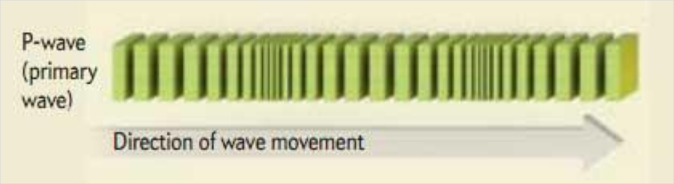

Figure 1: P-wave (Allen, 2011a)

S-waves**:** S-waves, or shear waves, oscillate sinusoidally and move perpendicular to their direction of travel. These waves cause most of the earthquake-induced damage such as the destruction of buildings and landslides. Unlike p-waves, s-waves cannot travel through gas or liquid and travel at a slower rate of 2-5km/second (P-Waves and S-Waves, 2009). For an efficient earthquake warning system, it is critical that earthquake technology can quickly detect the p-waves and issue a warning before the arrival of these s-waves.

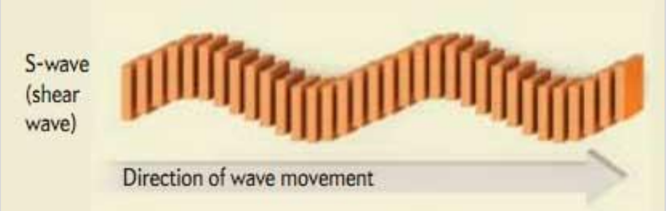

Figure 2: S-wave (Allen, 2011a)

Seismographs are used to detect and differentiate between these two types of seismic waves. Because earthquakes are not limited to any particular region of Japan, JMA has installed over 1,000 seismographs throughout the entire country for earthquake detection (Hoshiba, et al., 2011; Talbot, 2011). When a p-wave is detected by a seismograph, the wave's frequency and amplitude is recorded for four seconds in order to decrease the possibility of false positives caused by local activity such as road traffic or construction (Ryall, 2008). This data is then sent to JMA's Earthquake Phenomena Observation System (EPOS), where algorithms are used to analyze and estimate the epicenter location (the point on the earth's surface directly above the hypocenter) and magnitude. For a successful early warning system, it is critical to quickly assess the earthquake's parameters and hazards in real-time prior to the arrival of the s-waves and the subsequent damage caused by these waves. Because this type of detection issues a warning after the earthquake has released its initial seismic waves, the EEWS is most useful for regions that are located at least 100km from the earthquake's epicenter. This distance translates into an approximately 20-50 second warning. The area located within the 100km radius is known as the *blind zone* and is too close to the hypocenter to receive a warning. Because of this blind zone, it is important that this system is complemented with on-site earthquake detection mechanisms, particularly in heavily populated urban areas or near critical factories handling dangerous machinery or chemicals. In this way, earthquake detection relies not only on JMA's seismographs, but also locally installed and operated seismograph devices, which helps to improve both accuracy and reliability of earthquake detection for the purposes of disaster mitigation.

In addition to seismographs, another important tool necessary for earthquake detection is seismic intensity meters. Seismic intensity is a measure of the strength of the seismic waves and represents the degree of shaking occurring at a specific location. Thus, Japan's network of seismographs, which calculates the earthquake's epicenter location and magnitude, is supplemented by a network of seismic intensity meters that are used to predict the damage radius and maximum expected seismic intensities at each affected region. Each seismic intensity meter collects the current seismic intensity in order to predict the maximum degree of shaking expected during the peak ground acceleration of the earthquake. Because seismic intensity is directly related to expected damage, this information is important in order to determine whether or not to alert disaster management authorities or whether to issue a warning to the general public. In addition, seismic intensity measurements are important for damage prediction and are used to automatically mobilize emergency responses and enable countermeasures for disaster mitigation (Kamigaichi et al., 2009). By utilizing both seismographs and seismic intensity meters, Japan is able to collect enough data to quickly determine appropriate countermeasures.

The EEWS collects seismic intensity data from the 619 seismic intensity meters operated by JMA as well as the over 3,600 seismic intensity meters operated by the National Research Institute for Earth Science and Disaster Prevention (NIED) (777 units) and local governments (2,842 units) (JMA, 2011d). The collected seismic intensity data is measured using Japan's Shindo scale (compared to the Mercalli Intensity scale used in the United States).

Japan's Shindo Seismic Intensity Scale: The 10-degree seismic intensity scale used in Japan is measured in units of *shindo* (震度) and ranges from 0 to 7, with 7 being the upper limit. These shindo measurements are rounded off to the nearest integer except for 5 and 6, which are divided into 5-lower (4.5-4.9), 5-upper (5.0-5.4), 6-lower (5.5-5.9), and 6-upper (6.0-6.4) (Hoshiba et al., 2011). The shindo scale describes the degree of shaking that occurs at a specific location and takes into consideration the amplitude, frequency, and duration of seismic motion at any particular point on the Earth's surface. It is important to understand Japan's shindo scale because the EEWS transmits two different types of warnings depending on the predicted shindo of the earthquake.

Earthquake Warning Dissemination

Once an earthquake's predicted magnitude, location, and seismic intensities have been calculated, this data is transmitted in real-time to EPOS, where it is analyzed to determine whether to broadcast an earthquake warning. The distribution of these warnings relies on the fact that seismic waves travel more slowly than data transmitted over a telecommunication system. Ground tremors caused by s-waves travel at an average of 2-5km/second compared to electromagnetic signals used in telecommunication, which travel near the speed of light. This allows electronic warnings to reach residents before the arrival of the more violent seismic vibrations, giving people extra seconds to prepare.

In order to enable more targeted dissemination of warnings, JMA has divided Japan into 188 forecast regions. Each region contains dozens of forecast points where seismic intensity meters are used to determine the seismic intensity at that location (Doi, 2010; JMA, 2011e).

Because multiple detection points are used within each region, the forecast point with the maximum predicted value is used to represent the seismic intensity for that region. Based on this predicted seismic intensity value, JMA transmits two types of earthquake warnings: *advanced notice forecasts* and *earthquake alert warnings*.

Advanced Notice Forecasts (Alerts for Advanced Users)

If at least one seismic intensity station detects a seismic intensity of 3 or greater, or if a seismograph predicts an earthquake of magnitude 3.5 or greater, then an advanced notice (地震動予報) or *forecast* (予報) is issued (Hoshiba et al., 2011; JMA, n.d.a; Matsumura, 2011). These forecasts are only issued to expert users and include information about the time of the earthquake outbreak, the estimated magnitude of the earthquake, and the expected seismic intensity for that region. If the seismic intensity is expected to be greater than 4, then the forecast also lists the names of all affected regions and their respective estimated seismic intensities and s-wave arrival times (Doi, 2010; JMA, 2011). Because accuracy of these seismic predictions increases as more data becomes available, JMA continually sends out updated advanced notice alerts with increasing accuracy. On average, five to ten reports are issued within the first 60 seconds of detection. However, if a second seismograph station does not also trigger an advanced notice alert within the first 10 seconds of the first forecast, then a "cancel report" (キャンセル報) is reported (JMA, 2011; Kamigaichi et al., 2009).

For distributing advanced notice forecasts to its limited set of subscribed users, recipients must have advanced computer terminals specifically configured to receive this information. Forecasts are targeted to expert users who require this information to immediately take precaution, such as school administrators or doctors conducting surgery (Birmingham, 2011). Additionally, these forecasts are also received by systems that are pre-automated to perform countermeasures, such as halting high-speed trains or backing-up and saving vital computer information in data centers (Matsumura, 2011). Because these recipients are specifically contracted with JMA to receive these forecasts, JMA is able to educate and train these users on the technicalities of the EEWS so that they can most effectively make use of this type of alert. In conjunction with these forecasts from JMA, epicenter distance and earthquake magnitude are also calculated locally at each individual user's terminal. Using a local and remote system increases the accuracy of the data, while also minimizing unnecessary and costly disruptions caused by false positives. Examples of these advanced users include railway companies, construction sites, elevator control facilities, apartment complexes, schools, hospitals, and shopping malls. As of 2009, 52 out of the country's 204 railway companies have installed earthquake forecast receivers to pre-automate the slowing down of trains during an earthquake (Kamigaichi, et al., 2009). Because the EEWS detects earthquakes in the early stages of fault rupture, there is a critical trade-off between time and accuracy in efficiently sending out earthquake alerts. However, by differentiating advanced users from the general public, JMA can quickly disseminate these warnings with a more lenient threshold of accuracy because these end receivers are equipped with onsite seismic technologies and are trained in the technical implementation and limitations of the EEWS.

However, these forecasts still have much room for improvement. During the first 3 years since the beginning of the EEWS, JMA issued 30 false positives out of the total 1,713 advanced alert forecasts issued (1.7513% failure rate). Many of these failures were caused not only by underestimation of earthquake magnitude, but also human error and instrumentation defects. As a result, JMA encourages its users to implement on-site seismometers to be used in conjunction with JMA's EEWS notifications. For instance, Miyagi Oki Electric Company, a manufacture of semiconductors, has installed its own p-wave seismographs in its plants to supplement data from JMA. As of 2009, 650 on-site seismometers have been installed across Japan, 500 of which are located in schools (Allen, Gasparini, Kamaigaichi, & Böse, 2009; Miyagi Oki Electric, 2006). These on-site seismographs in conjunction with JMA's earthquake alerts are critical to automatically halt activity and locally broadcast alerts to its employees and customers.

Earthquake Alert Warnings (Alerts for the General Public)

If a seismic intensity of 5-lower or greater has been detected by at least two seismograph stations, then an earthquake alert warning (地震動警報) or *warning* (警報) is issued (JMA, n.d.a). Because these warnings are broadcasted to the general public an earthquake alert warning requires detection by at least two stations in order to decrease false positives. Similar to the advanced notice alerts, JMA sends updated warnings to the general public within 60 seconds of the first warning as new data is collected. The first warning only includes the names of all forecast regions with a seismic intensity of 3 or more. Successive warnings are updated with the location of the earthquake's epicenter, estimated magnitude, and the names of all regions with a predicted seismic intensity of 4 or greater (JMA, n.d.b.; Matsumura, 2011). However, unlike the advanced notice alerts, warnings to the general public are not canceled even if the detected seismic intensity at that location falls below the 5-lower threshold (Hoshiba et al., 2011). This is to avoid confusion in the event that the predicted seismic intensity rises again.

JMA uses media such as outdoor loudspeakers, television and radio networks as well as cellular broadcasting to relay earthquake warnings as quickly as possible to the general public. As of 2005, 70% of municipalities in Japan have developed a loudspeaker system by installing loud speakers on building roof-tops, on the streets, and on official public relation vehicles (Early Warning Sub-Committee, 2006). Nippon Hoso Kyokai (NHK), also known as the Japan Broadcasting Corporation, is Japan's national public broadcasting organization and operates two terrestrial television services, two satellite television services, and three radio networks. Under the Meteorological Service Act (Act No. 115, 2007), NHK is required by law to broadcast emergency reports including earthquake early warnings on all of these networks. These warnings use text as well as sound and are broadcasted in five languages including Japanese, English, Mandarin, Korean, and Portuguese (JMA, n.d.a). In addition to NHK, 122 out of Japan's 127 television companies, 24 out of 47 AM radio companies, and 25 out of 53 FM radio companies also broadcast these emergency warnings (Kamigaichi, 2009). Because Japan has a large aging population, it is important that these traditional forms of communication are used to broadcast this information to ensure that all demographics receive these warnings.

However, the traditional dissemination methods for these warnings have limitations. Television network and radio coverage is limited and requires that these devices are turned on for this information to be received. This is especially problematic at night when most of these devices are turned off. To mediate this shortcoming, JMA also uses Short Message Service-Cell Broadcast (SMS-CB) which is a method to push warning messages to the public. SMS-CB is a one-to-many geographically focused messaging service that can simultaneously send a mass text warning to all mobile devices distributed over a land area called a *cell* (Udu-gama, 2009). Each cell is operated by a cell tower and requires both cell broadcasting capability in the cell tower and handheld device. Most cell phone operators have enabled SMS-CB in both cell towers and phones for this purpose. Users must enable the cell broadcasting capability in order to receive these broadcasted warnings. Similar to television networks, distribution via SMS-CB is not affected by the number of recipients, thus communication efficiency is not hindered during peak hours. This is because SMS-CB's network uses channels that are allocated solely for the purpose of relaying cell broadcast messages and does not conflict with other services such as SMS-point to point (SMS-PP) text messaging. However, delivery delays may occur in areas with poor network coverage and this service can be disrupted if the cellular system is damaged or disconnected. These messages are also sent to recipients based on geographic location and do not require a cell phone number in order to be sent and received and thus protect the privacy of the public users. It is also very difficult for outside users to generate cell broadcast messages, which reduces the possibility of generating counterfeit emergency alerts (Sillem, Wiersma, 2006). By also using cell broadcasting, JMA is able to relay important earthquake warnings to residents of affected areas without solely relying on television and radio networks. Furthermore, earthquake early warning alerts must be localized for specific regions because the content of each warning will vary by region. As a result, the localized nature of cell broadcast is useful for this purpose. In addition, because the overall goal of these warnings is to alert the public prior to earthquake destruction, cell towers will still be operating at the time of dissemination. As of 2009, 21 million cell phones in Japan have the capability of receiving earthquake early warnings using cell broadcast networks. In addition, three of Japan's major cell phone carriers, NTT Docomo, au (KDDI and Okinawa Cellular), and Softbank, support this service free of charge (Kamigaichi, et al., 2009; NTT DoCoMo Inc., KDDI Corp., 2007). This method is particularly useful in Japan where cell phone use is very high[1] and 97.4% of cell phone users are subscribed to one of these three cell phone carriers (Telecommunications Carriers Association, 2011).

Ideally, a method that can accurately predict earthquakes within the time frame of minutes, hours, or even days, would be the best system for earthquake preparation. However, until this type of technology is made available, JMA's EEWS is the next best method for earthquake preparedness because it analyzes earthquake data in real-time to predict the location and severity of the damage that will result. By issuing a warning a few seconds before the ground begins to shake, users will have time to prepare for the onset of an earthquake by taking precautionary measures such as turning off gas stoves, moving away from windows, or turning off heavy machinery.

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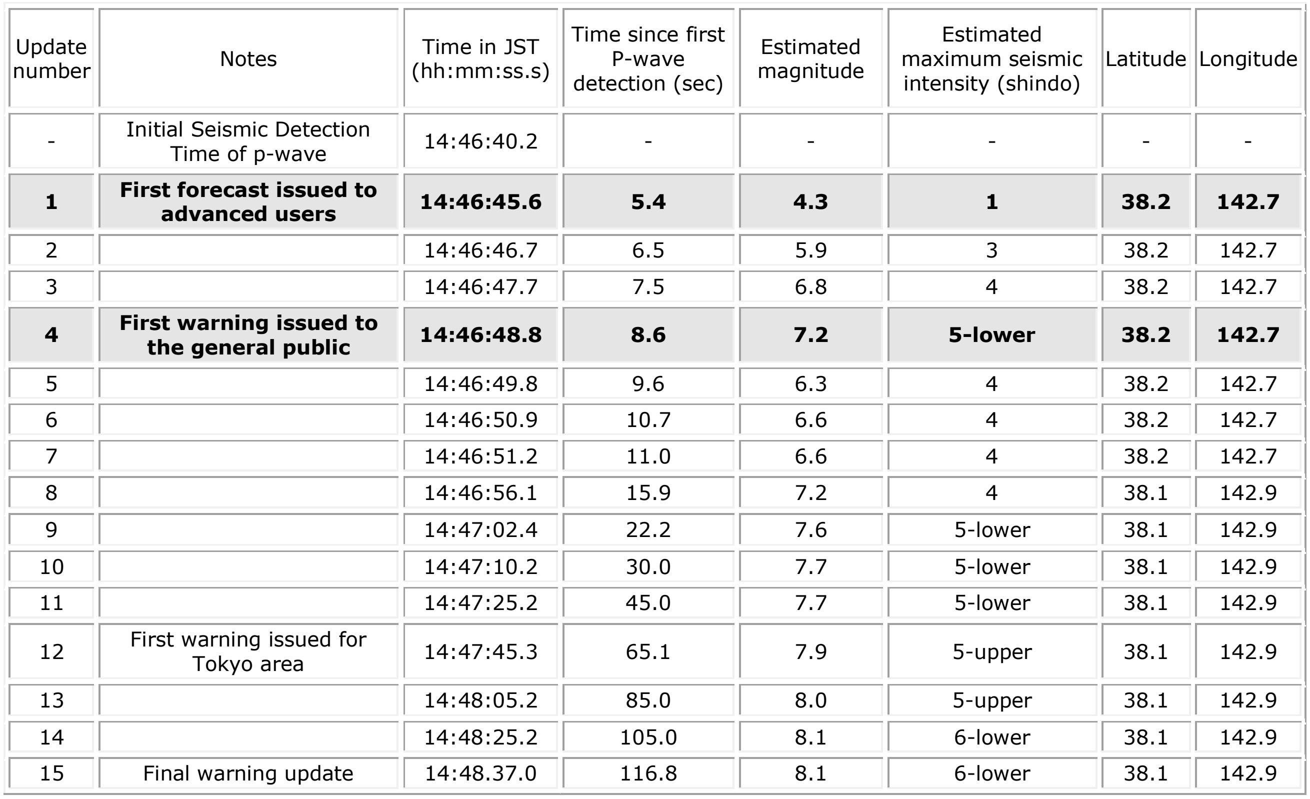
[1] As of March 2011, Japan has 119.5 million cell phone users and a total population of 127.9 million (Japan Statistics Bureau, 2011; Telecommunications Carriers Association, 2011)

III. The Earthquake Early Warning System during the Tohoku Earthquake

At 14:46:23 JST on March 11th, 2011, a 9.0 magnitude earthquake with a maximum seismic intensity of 7 occurred on the north eastern Pacific coast of Honshu, Japan. The seismograph station at Ouri in Ishinomaki City was the first of over 380 seismic stations across Japan to record seismic movement at 14:46:40.2 JST (Risk Management Solutions Inc., 2011). As shown in table 1, the first earthquake forecast was issued to advanced users 5.4 seconds after the initial detection of p-waves. An earthquake warning was issued to the general public was issued 3.2 seconds after this forecast. A total of 15 forecasts, warnings, and updates were issued within the two minutes of the initial seismic detection. The first warning issued to the public was broadcasted to the Sendai area in central Miyagi prefecture and predicted an earthquake of magnitude 7.2 and seismic intensity of 5-lower (Hoshiba et al, 2011; JMA, 2011a). This warning arrived 15 seconds prior to the s-waves arrival in Sendai, which is located 129km west of the earthquake's epicenter. Tokyo, located 373km southwest from the epicenter, received 65.1 seconds of warning before the ground began to shake (Henn, 2011; USGS, 2011a).



Update number	Notes	Time in JST (hh:mm:ss.s)	Time since first P-wave detection (sec)	Estimated magnitude	Estimated maximum seismic intensity (shindo)	Latitude	Longitude
-	Initial Seismic Detection Time of p-wave	14:46:40.2	-	-	-	-	-
1	**First forecast issued to advanced users**	**14:46:45.6**	**5.4**	**4.3**	**1**	**38.2**	**142.7**
2		14:46:46.7	6.5	5.9	3	38.2	142.7
3		14:46:47.7	7.5	6.8	4	38.2	142.7
4	**First warning issued to the general public**	**14:46:48.8**	**8.6**	**7.2**	**5-lower**	**38.2**	**142.7**
5		14:46:49.8	9.6	6.3	4	38.2	142.7
6		14:46:50.9	10.7	6.6	4	38.2	142.7
7		14:46:51.2	11.0	6.6	4	38.2	142.7
8		14:46:56.1	15.9	7.2	4	38.1	142.9
9		14:47:02.4	22.2	7.6	5-lower	38.1	142.9
10		14:47:10.2	30.0	7.7	5-lower	38.1	142.9
11		14:47:25.2	45.0	7.7	5-lower	38.1	142.9
12	First warning issued for Tokyo area	14:47:45.3	65.1	7.9	5-upper	38.1	142.9
13		14:48:05.2	85.0	8.0	5-upper	38.1	142.9
14		14:48:25.2	105.0	8.1	6-lower	38.1	142.9
15	Final warning update	14:48.37.0	116.8	8.1	6-lower	38.1	142.9

Table 1: Real-time estimates of the epicenter location, parameters and maximum seismic intensity generated by EEWS (translated and adapted from JMA, 2011a).

These warnings were broadcasted to the general public using television and radio networks and were also sent to approximately 52 million people on their cellular devices (Allen, Yamada, Kanamori, & Karause, 2011). The contours in figure 3 represent the relative warning time between the delivery of the earthquake alert and the s-wave arrival in seconds. The shaded region within the 0 second contour is the blind zone in which no warning was available due to its proximity to the epicenter.

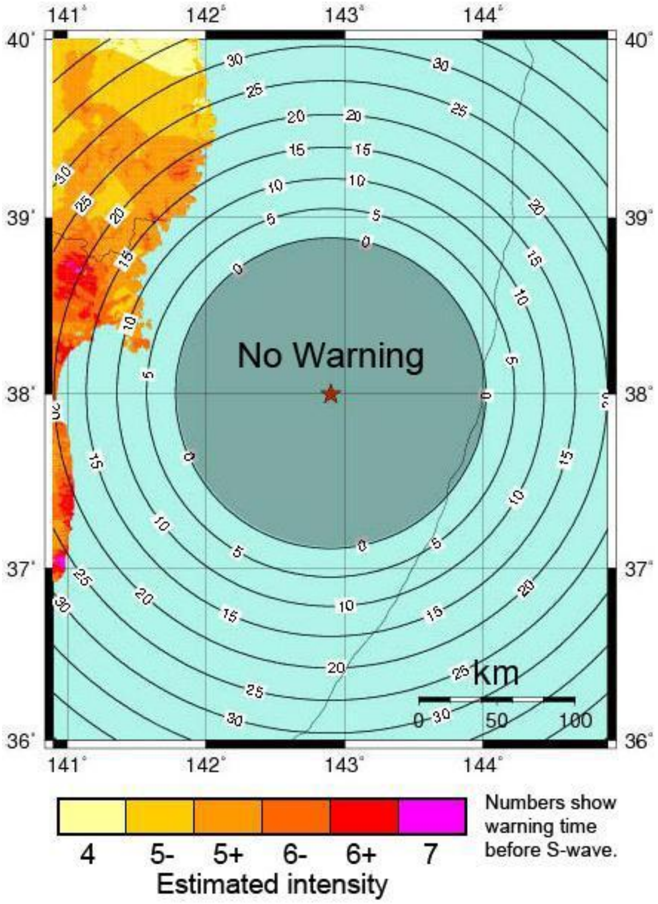


Figure 3: A map of the northeastern coast of Japan near the Tohoku region depicting the warning time in seconds from when an earthquake early warning was issued and the arrival of the s-waves (adapted from JMA, 2011b).

The advantages of JMA's EEWS's have been made clear by the numerous first person-accounts and YouTube videos depicting the benefits of having extra preparation time before the ground began to shake (Kirschke, 2011; Real-time Earthquake, 2011; Tonks, 2011; Yuanzency, 2011). University of Sendai professor Kensuke Watanabe received a warning alert on his cell phone prior to the earthquake. This warning gave him enough time to instruct his students to take cover under desks and as a result none of his students was hurt during Japan's worst recorded earthquake (Birmingham, 2011). Additionally, JMA's advanced notice forecasts were sent to several critical companies which triggered automatic shutdown of facilities and infrastructure. For instance, forecasts sent to East Japan Railway Company (JR East) caused eleven Tohoku Shinkansen bullet trains to automatically come to a halt seconds before the ground began to shake. Other companies like Otis, an elevator manufacturing company was also able to shut down 16,700 elevators in affected areas as soon as the earthquake forecast was received (Vervaeck & Daniell, 2011b). In addition, 40 of the 42 elevators in Tokyo's Metropolitan Government Building buildings (東京都庁舎), which range from 41-243 meters in height, also automatically stopped at the nearest available floor and shutdown to allow for evacuation as a result of JMA's earthquake warnings (Vervaeck & Daniell, 2011a; Tokyo Metropolitan Government, 2010). Although specific statistics on the number of survivors from the earthquake are still be collected, these personal accounts reinforce the life-saving benefits of having a warning technology.

Although Japan's EEWS was successful in issuing warnings during the Tohoku earthquake, this system was not infallible. The warning system algorithm assumes that the source of an earthquake is a single point (Olson, Liu, Faulkner, Chandy, 2011). However, in the case of the Tohoku earthquake, the fault line extends hundreds of kilometers on the subduction zone plate boundary, parallel to the eastern coast of Japan. This fault slipped over an area of 300km long and 150km wide and resulted in fault movement of 30-40meters (USGS, 2011a). As a result, the system was unable to detect the two-dimensionality of the fault-line and underestimated both the magnitude and affected regions (Cyranoski, 2011; Yamada, 2011). Figure 4 shows the observed seismic intensity of the Tohoku earthquake (left) compared to the predicted seismic intensity computed from the last warning (warning 15 in table 1) issued by JMA (right). From this diagram, it is clear that JMA's final prediction based on the seismic signals triggered a warning for a limited region with an underestimated earthquake magnitude of 8.1. Many scientists argue that that data from Japan's extensive high-sensitivity accelerometer network cannot accurately estimate the magnitude of the earthquake based solely on the initial seven seconds of the seismic movement data (Hoshiba & Iwakiri, 2011). Forecasted seismic intensity has the potential to be miscalculated by a magnitude of one or two (Honma & Ichikawak, 2008), which can have serious implications since the system may fail to send an alert if the magnitude is underestimated.

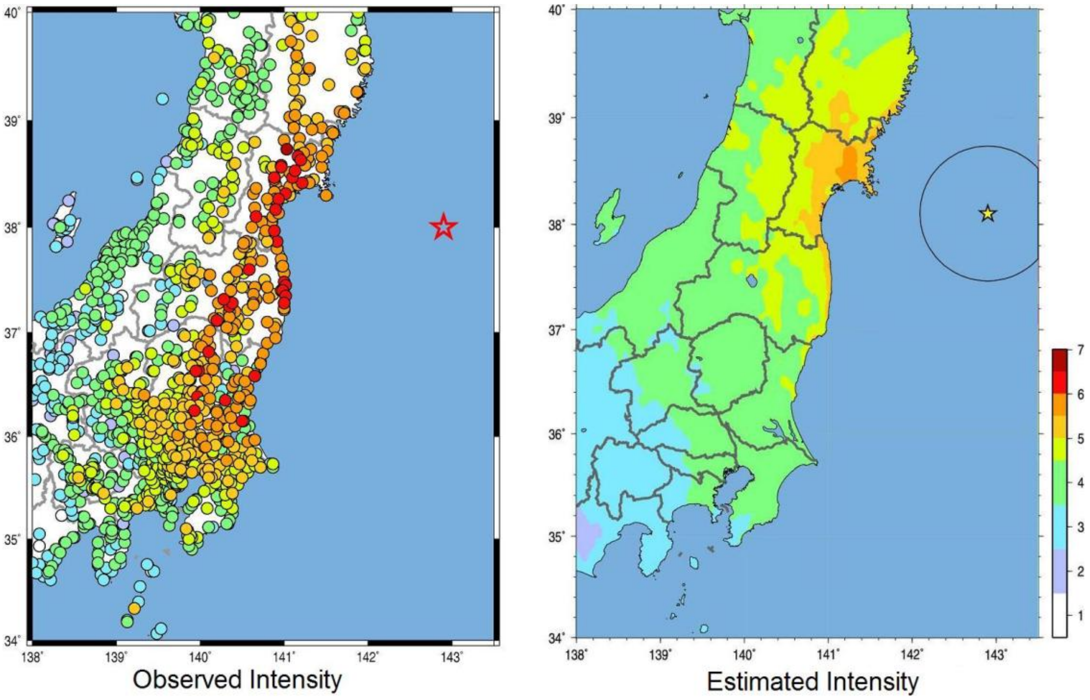


Figure 4: Japan Meteorological Agency’s estimated seismic intensity computed based on the last warning issued by the EEWS (right); the actual observed seismic intensity (left)

Additionally, after the mainshock of the earthquake, the system was confounded due to power failures, wiring disconnections, and the numerous aftershocks. This generated several false positives and the system also failed to detect several significant aftershocks during the three hours following the earthquake’s initial rupture (Hoshiba et al., 2011; Yamada, 2011). These negative repercussions continued for 19 days following the main earthquake on March 11th. During this period, 34 out of 45 total warnings issued were false positives (JMA, 2011c). Although it is difficult to numerically quantify the both successes and the failures of the EEWS during the Tohoku Earthquake, it is important to critically analyze its performance in order to continue to improve upon this existing system.

IV. An Earthquake Early Warning System for Other Countries

With Japan at the forefront of earthquake early warning technology, it is important to look at it as an example model for other earthquake-prone countries. Evaluating this system in the context of the recent Tohoku earthquake gives scientists an opportunity to analyze the advantages as well as shortcomings of Japan’s EEWS. Despite the many successes of the EEWS, it is also critical to understand that there is no one-size-fits-all system that can be successful in all regions of the world. Although Japan’s current system serves as a model for earthquake warning technology, other countries must also take into consideration other factors in order to implement a similar technology. Specifically, the success of Japan's warning system relies not only on its sophisticated technology, but also the country's history of strict building codes, its access to a dense seismographic network, and its culture of disaster preparedness. Understanding these factors will make it more feasible to adapt and implement a similar system in other countries.

Criteria 1: Dedication to Strict Building Codes

One critical component to Japan's earthquake preparedness is the country's stringent building codes that dampen seismic vibrations and allow buildings to sway in order to prevent collapse. Currently, Japan's buildings are ranked among the sturdiest buildings in the world, but it took several centuries and numerous iterations before Japan was able to attain this level of sophistication. The evolution of Japan's architecture can be heavily attributed to Japan's long history of earthquakes. Each of Japan's devastating earthquakes has served as a vital reinforcement to the necessity of strict standards for building construction. In 1995, the widespread damage caused by the 6.9 magnitude Great Hanshin-Awaji Earthquake (popularly known as the Kobe earthquake) revealed the urgent need for Japan to reevaluate the seismic performance of buildings. The damage caused by this earthquake resulted in 5,373 casualties and over $100 billion in property damage. However, a portion of the damage was mitigated by the revised requirements to the Japanese Building Standard Act that were put into place in 1981 as a direct result of the 7.4 magnitude earthquake in Miyagi prefecture (Ghosh, 1995). The benefit of these building code modifications is evident in the breakdown of building damage in relationship to construction date as seen in figure 5.

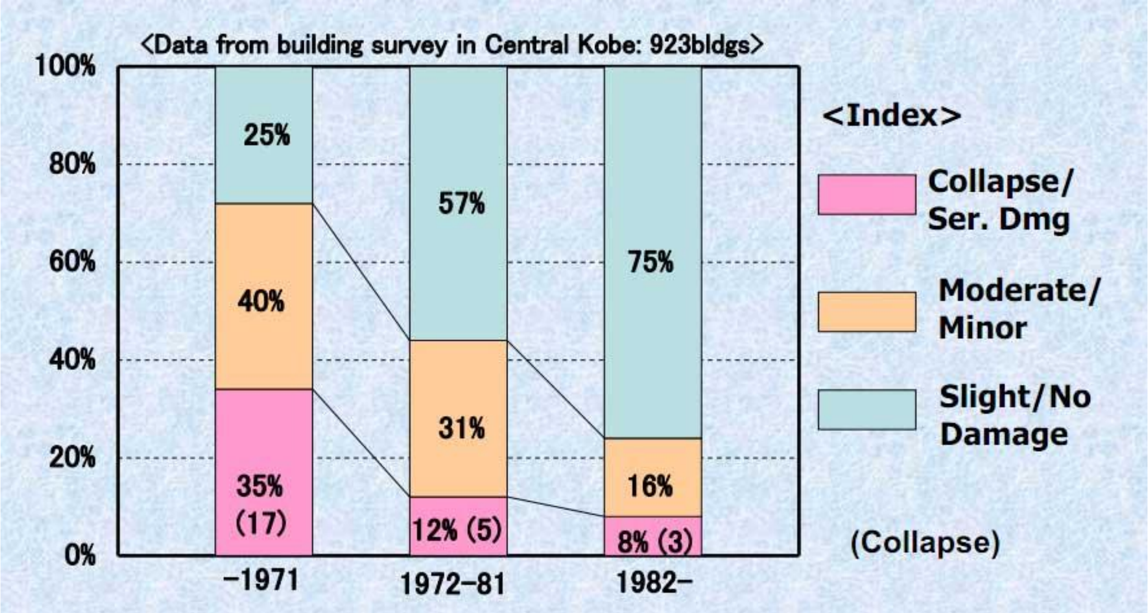


Figure 5. Damage statistics of 932 buildings located in Central Kobe as a result of the Kobe Earthquake in 1995. Damage levels are classified as collapse/serious damage, moderate/minor damage, slight/no damage and are compared by construction year (Tsunozaki, 2006).

As has been the trend throughout Japan's earthquake history, the damage and death caused by the Kobe earthquake fueled another reassessment of building codes, which were soon replaced by stricter standards. This continuous evolution of building codes, although triggered by destruction and large-scale casualties, continues to serve as a method to check that Japan's current architecture can withstand its destructive earthquakes. The billions of dollars as well as decades of research and development in structural technology is just another component that has played a crucial role in Japan's resilience during the Tohoku earthquake. Japan, just as it will continue to have earthquakes, will also continue to advance its building standards. Although it has taken years to establish, this sophisticated infrastructure is another key component to the success of Japan's EEWS. Without these earthquake-proof buildings as the first line of defense, a warning system would become nearly futile in reducing disaster risk.

Criteria 2: Access to a Dense Seismographic Network

Another component to the success of Japan's EEWS is that it has the world's densest network of seismic devices to measure the vibrations and ground movement caused by earthquake waves. These devices are evenly distributed throughout the country's 378,000km^2 land area with approximately one station for every 20km radius (Japan Statistics Bureau, 2011; Okada et al., 2004). However, for countries that do not have this infrastructure already in place, there is a steep capital investment to purchase, install, and maintain a network of seismograph stations. Each of these self-contained stations requires a seismometer, a computer, a GPS, radio equipment, and a stable power source, all of which can take several days to install and require high maintenance expenses (Cochran, Lawrence, Christensen, & Chung, 2009a). The high costs, time, and overhead prevent many countries from developing a reliable seismographic network necessary for an early warning system. For countries in which extensive seismograph stations are not feasible, researchers are investigating cheaper alternatives that take advantage of personal computers to collect seismic activity data.

In order to overcome the challenge of establishing a dense seismographic network, many researchers have been investigating the use of low-cost seismometer alternatives. An example of this is the Quake-Catcher Network (QCN) which was developed by Stanford University in 2008. QCN relies on volunteers to use the built-in triaxial micro-electro-mechanical systems (MEMS) accelerometers in laptop computers in order to detect ground motion. These accelerometers are sensitive enough to ascertain the direction of the earth's movement for earthquakes with magnitudes $3.1 \leq M \leq 5.4$ (Cochran et al., 2009a). By using these built-in accelerometers, ground accelerations can be recorded and can detect an earthquake within tens of kilometers and with a magnitude greater than 3.0 (Cochran et al., 2009a). Utilizing the internet capabilities of the laptop, this data is then transmitted to a central server. Volunteers also have the option to purchase a cheap MEMS accelerometer for $49 (qcn.stanford.edu) that can be connected to a desktop computer. All sensors are connected to a distributed system in which each autonomous computer uploads important information to the centralized server such as the sensor location, time of detection, and the amplitude and period of the ground motion,. The central server clusters computers based on geographical location so that data within the same cluster can be compared to determine whether a trigger was an isolated event caused by local noise or whether it was caused by seismic activity in a particular region. Because the spatial distribution of these computers is critical in analyzing this data, this algorithm must be able to accommodate for a continuously evolving network in which nodes—in this case the volunteers—are removed and new nodes are added.

QCN is beneficial because it has the potential to exponentially increase its network size while still providing near real-time earthquake detection because each computer is responsible for collecting and analyzing its own recorded data. In order to determine whether an event is a potential earthquake, the ratio of the current acceleration to the average acceleration over the previous minute is calculated to determine whether it exceeds a difference of three standard deviations. This technique is known as short-term average to long-term average ratio (STA/LTA) (Cochran et al., 2009a). Because data is analyzed on each individual computer, only minimal data needs to be transmitted to the central server. This approach differs from other methods that continuously upload raw data to a central server where it is then aggregated and processed (Cochran, Lawrence, Christensen, & Jakka, 2009b). This is especially important for a system that uses a less sophisticated seismic sensor because detection accuracy is heavily dependent on the density of the seismic network. In this way, low-cost home-based accelerometers can be used as a cheap alternative to professional-grade seismometers. Although there are difficulties because the lower cost comes at a price of lower quality data, algorithms can be created to differentiate between noise and useful earthquake activity. Furthermore, as personal technologies with builtin-MEMS accelerometers become more popular such as smart phones and tablets, this type of low-cost seismic network will be an invaluable method to collect and analyze seismic data.

Criteria 3: Culture of Disaster Preparation

Lastly, a third component to the success of Japan’s EEWS relies on the degree to which the society itself has taken precautionary measures to prepare for earthquakes. By taking precautionary measures to educate and train the public, Japan has developed a strong culture of preparedness and resilience in the wake of natural disasters. This hard-earned culture of earthquake preparedness has been embedded in Japan on both the school and community level. In Japan, earthquake education begins in kindergarten and includes a curriculum of evacuation guidelines, earthquake causes and effects, and hands-on practical training (Shaw, Shiwaku, Kobayashi, Kobayashi, 2004). Earthquake safety and protocol is heavily integrated into the academic curriculum from elementary through high school. Additionally, schools are equipped with special computer that receive JMA’s earthquake warnings. Depending on the severity of the earthquake warning, these computers can be used in evacuation or training mode. Additionally, a third mode is available solely for education purposes. Evacuation mode is used to broadcast JMA warnings with seismic intensity of 4 or greater using both voice and visual warnings on computer terminals. Training mode is used when a JMA warning is issued with seismic intensity of 3 or lower in order to practice evacuation drills. The system broadcasts these warnings during mild earthquakes with low danger-risk in order to simulate an environment in which students do not know an earthquake is about to occur. The final mode, education, is used as a classroom tool to provide pictures of earthquake damage and disaster response animations to educate students on how to react during a seismic event. This training is also supplemented by leaflets and educational DVDs on earthquake safety used in the classroom (Motosaka, Homma, 2009). Additionally, on the first day of the Japanese academic school year, students of all ages are required to participate in an earthquake drill. By integrating earthquake preparedness into the curriculum, Japan can ensure that its students will be able to stay calm and follow evacuation guidelines in the advent of an earthquake.

Another feature of Japan's earthquake resilience is that earthquake training does not end in the classroom and extends into the workplace and community. Numerous companies throughout the country have regularly scheduled earthquake drills that are mandatory for their employees. This is also supplemented by the National Disaster Prevention Week (防災の週間) hosted annually since 1960 during the first week of September. This nationally recognized week was created to commemorate the 7.9 magnitude Great Kanto Earthquake of 1923 that struck the Kanto region of Honshu resulting in 142,800 deaths (USGS, 2010). This week was established to not only honor the numerous casualties from the Kanto earthquake, but to also spread awareness about typhoon, tsunami, and earthquake preparedness and acknowledge distinguished members of the community. These various activities last throughout the entire week of September. However, the most important event of the week is National Disaster Prevention Day (防災の日) on September 1st, which culminates in a national-level drill with the cooperation of the prime minister and local governments in order to simulate a natural disaster scenario (Cabinet Office, 1982). This day is also a reminder and opportunity for public and private buildings to review their evacuation protocols as well as ensure that families are equipped with emergency earthquake survival kits and replace batteries in flashlights. This year, National Disaster Prevention Day was held nationwide on August 30th to September 5th, 2011 and was the first national drill since the Tohoku earthquake. According to Japan's Cabinet Office, 35 of Japan's 47 prefectures and 517,000 people participated in the nationwide drill that simulated an earthquake in Tokai, Tonankai, and Nanaki, with a large earthquake in Kansai and Shikoku regions. The drill also triggered a practice tsunami warning requiring coastal areas to evacuate to higher ground (Asahi, 2011). Because earthquakes can occur anywhere in the country at any time, it is important that Japan emphasizes a culture that is proactive about their earthquake preparedness.

However, it is not just enough for Japan to educate its citizens about earthquake preparation. In order to maximally benefit from its $500 million earthquake early warning system, Japan must also ensure that its people fully understand the meaning of these warnings. As a result, in 2006 JMA launched a nationwide educational campaign and public outreach prior to the launch of its EEWS. The goal of this initiative was to train individuals how to interpret and appropriately respond to JMA's earthquake early warnings. Additionally, this campaign sought to make the public aware of the possibility of false warnings, underestimation of magnitude and seismic intensity, or any other unexpected technical limitations of the system. Without this campaign, warning messages may have caused adverse effects of confusion for its recipients. JMA also distributed educational brochures and leaflets to community members (www.jma.go.jp/jma/en/Activities/eew.html), broadcasted videos explaining the technical principles of the EEWS, displayed posters with appropriate earthquake responses, held nationwide seminars, and maintained an accessible web page containing relevant information (www.jma.go.jp). In May of 2007 JMA conducted a survey of approximately 2,000 Japanese between the ages of 20 to 69 throughout the country. The results of their study showed that 84% of the public knew of the new EEWS and 39% understood the implementation of the system. Additionally, 86% of surveyors understood the possibility of error in JMA's reported seismic intensity (JMA, 2007a). It was only after JMA was able to comfortably determine that the people of Japan understood the new EEWS that they began to broadcast warning messages to the public on October 1st, 2007. Because earthquakes occur unexpectedly and propagate rapidly, it is important that the residents of Japan can quickly understand these warnings and take appropriate precautionary measures.

The custom of natural disaster preparedness is deeply embedded into the culture of Japan. This is partly due to Japan's high frequency of earthquakes, but also because Japanese culture is more proactive due to its long history of earthquakes. Japanese people are also very detail-oriented, precise, and cautious, which fosters a mindset of disaster preparation. These societal characteristics are a critical factor in the success of an early warning system. Without this, earthquake warnings issued to the public may result in widespread panic taking away from any lead time a warning would have allowed for.

With the ability to save lives and prevent injury, an earthquake warning system seems important if not necessary for other earthquake-prone. However, as in the case with Japan, a certain amount of ground-work must first be put in place in order for a warning system to be maximally effective. Earthquake technology must be complemented with educated citizens and carefully engineered earthquake-proof structures in order to be successful. Just as one learns from ones past experiences, the rest of the world can look towards Japan as a model system for implementing earthquake disaster mitigation. By understanding the underpinnings of the technology and the surrounding societal implications, other countries can use Japan as a model to develop and adapt a similar technology that will work best in its society.

VI. Conclusion

Natural disasters are not confined by boundaries. Not only were the vibrations of the Tohoku earthquake felt throughout the world, but the widespread destruction was witnessed and experienced by people from across the globe. International aid immediately spilled into Japan as the world came together to mourn the devastation of this deadly disaster while encouraging the people of Japan to begin moving forward. With the support of the international community, the Tohoku region and Japan as a country can begin to look forward towards the future. Just like the aftermath of the Kobe earthquake, the devastation in Tohoku will come hand in hand with the renewal of life and an immense opportunity for innovation. Similarly, Japan has an opportunity to step up as a global leader and share its knowledge and experience with earthquake technology to the rest of the world. With only a handful of countries running a similar technology, many other countries prone to the destruction of these natural disasters could immensely benefit.

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