FEASIBILITY STUDY ON EARTHQUAKE EARLY WARNING SYSTEM FOR THE CITY OF LIMA, PERU, USING A NEWLY DEPLOYED STRONG-MOTION NETWORK

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ABSTRACT

Feasibility of earthquake early warning system (EWS) for the city of Lima, Peru, was investigated using seismic waveform data from the newly installed real-time strong motion observation network. We selected waveform data from 24 earthquakes (ML>3.5, depth<100 km) and estimated sizes and locations of the events using initial P-wave portions, based on the conventional approaches. For the estimation of earthquake magnitude, we determined "τ_c" parameter using 3 s time window after the P-wave onset. We found a reasonable correlation between the estimated and catalogue magnitudes for earthquakes in the vicinity (hypocentral distance<130 km). The hypocenter locations were determined with the detected P-wave arrival times. To investigate the accuracy of existing ground-motion prediction equations (GMPEs) in a real-time scheme, we selected two GMPEs for subduction zone earthquakes to compare the predicted peak ground accelerations (PGA) with observed ones. We also confirmed that the size of blind zones of the EWS is not so large for most earthquakes and it is possible to give an alert to the city of Lima before S-wave arrivals, if a hypocenter location was accurately determined.

Keywords: Earthquake Early Warning System, Hypocenter, Peak Ground Acceleration, Blind zone.

1. INTRODUCTION

Peru is located in the most seismically active region of the world, called the Circum-Pacific belt or Pacific Ring of Fire. Lima City, the capital of Peru, experienced earthquakes and tsunamis frequently due to the location. The last large event in the city occurred in 1974 (Mw 8.0) and strong ground motions hit the coastal areas of Lima and Callao, causing severe damage. More than 40 years have passed since then and the probability of larger seismic events has been increasing. According to earthquake scenarios by Pulido et al. (2015), an Mw 8.9 earthquake in the central coast of Peru would directly affect Lima City is expected to occur. Earthquakes EWS can be used to prepare the citizens for the earthquake just before the strong ground shakings and reduce the casualty and economic loss. The purpose of this study is to examine the performance and expected problems of an earthquake EWS in Peru using data from the newly installed real-time strong ground motion network.

2. DATA

The data presented in this study was taken from the accelerograph network that belongs to the Japan Peru Center for Earthquake Engineering and Disaster Mitigation (CISMID). At each station strong-

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motion accelerograph REFTEK 130-SMA is installed at sample frequency of 200 Hz. There are 19 observation stations in Lima with 2-12 km station intervals. We selected earthquakes occurred in 2017 when the operation of the network started and obtained 347 records from 24 events. The magnitudes of the events are bigger than or equal to ML 3.5 and the focal depths are smaller or equal to 100 km. Table 1 is the list of the events used in this study.

Table 1. Catalog of the selected data after the magnitude estimation (data from the accelerograph network of CISMID).

Origin Time (UT)	Lat.	Lon.	Depth (Km)	Magnitude (ML)	No. Records	No. Select. Records
2017/5/3 19:05:49	-12.24	-77.40	32	4.0	9	9
2017/5/11 10:32:47	-12.07	-77.45	31	3.9	8	8
2017/7/8 20:07:24	-11.72	-77.37	73	4.8	12	12
2017/9/14 8:19:23	-11.91	-76.34	40	4.8	17	17
2017/9/15 4:10:36	-11.91	-76.33	18	4.4	16	5
2017/9/25 19:54:14	-11.96	-77.66	28	4.0	17	3
2017/10/22 0:09:13	-12.32	-77.34	36	4.7	17	17
2017/11/1 3:36:03	-11.77	-77.55	50	4.4	19	16
2017/11/24 2:24:26	-12.10	-77.55	46	4.1	19	12
2017/11/24 11:15:53	-12.09	-76.25	76	4.7	19	17

3. METHODOLOGY

3.1. Tauc (τ_c) parameter

In order to determine the size of an earthquake, it is important to know if the fault rupture stopped or is still growing, which is generally reflected in the period of the initial motion (Wu and Kanamori, 2005). We use an average of the period during the first motion (3 s of initial P-wave) to judge the source process. At first we computed the ratios of displacement $u(t)$ and the velocity $\dot{u}(t)$ waveforms using the vertical component of initial P-wave motions

$$r = \frac{\int_0^{\tau_0} \dot{u}^2(t)dt}{\int_0^{\tau_0} u^2(t)dt}. \tag{1}$$

The integration is over the time (0, τ_0) after the P-wave onset. We assigned 3 s for τ_0. According to Parseval's theorem, Eqs. (1) can be modified as

$$r = \frac{4\pi^2 \int_0^{\infty} f^2 |\hat{u}(f)|^2 df}{\int_0^{\infty} |\hat{u}(f)|^2 df} = 4\pi^2 \langle f^2 \rangle, \tag{2}$$

where $|\hat{u}(f)|$ is the amplitude spectra of $u(t)$ and $\langle f^2 \rangle$ is the average of f^2 weighted by $|\hat{u}(f)|^2$. Finally the parameter τ_c is defined as

$$\tau_c = \frac{1}{\sqrt{\langle f^2 \rangle}} = \frac{2\pi}{\sqrt{r}}, \tag{3}$$

and the relationship between the average τ_c and magnitude is formulated (Kanamori, 2005; Wu and Kanamori, 2005) as

$$M_{est}(\tau_c) = (4.525)\log\tau_c + 5.036. \tag{4}$$

3.2. Automatic Picking of P-wave

To detect the initial arrival of P wave automatically from the observed waveforms, we tested the automatic phase-picking algorithm proposed by Allen (1982). The detection of the event is accomplished by comparing a characteristic function or its short-term average (STA) with a threshold value (THR). If the STA exceeds THR, a trigger (P arrival) is declared.

3.3. Attenuation laws for estimating ground motion parameters

In Peru, there is no original ground motion prediction equation (GMPE) and various existing GMPEs derived in other seismotectonic environments have been tested. The frequently used ones are the attenuation law of Youngs et al. (1997) and Zhao et al. (2006).

3.3.1. GMPE of Youngs et al. (1997)

The relationship was developed based on regression analyses using data from 174 earthquakes in Alaska, Chile, Cascadia, Japan, Mexico, Peru, and Salomon Islands. They used events whose moment magnitude was larger than or equal to 5 and hypocentral distance from 10 to 500 km. There are two different functional forms of the relationship depending on site characteristics (soil site and rock site). Here we assumed that rupture distance is equivalent to hypocentral distance and source types of all earthquakes are interplate events.

3.3.2. GMPE of Zhao et al. (2006)

The authors used 4518 earthquakes in Japan, 208 earthquakes in Iran and Western USA. In the dataset the maximum focal depth is 162 km and the maximum source distance is 300 km. The events are classified into three source types; crustal, interplate and intraslab earthquakes. The maximum possible values for source depth is 25 km for crustal events, 50 km for interface events, and between 15 and 162 km for intraslab events. This equation also considers site conditions and the site amplification is evaluated depending on the NEHRP (National Earthquake Hazards Reduction Program) site classification.

4. RESULTS AND DISCUSSION

4.1. Magnitude estimation

The magnitude was computed using the software “tauc” provided by Dr. Masumi Yamada, which is based on the Tauc (τ_c) theory. We applied the software “tauc” for all the stations and events, considering two parameters, 0.2 Hz for the cutoff frequency of Butterworth high pass filter and 0.05 gal for acceleration threshold value.

After the processing for all the recordings (as is shown in Figure 1), we selected the data again because the estimated values of magnitude were largely overestimated for events whose epicentral distance was long and whose magnitude was small, due to low S/N ratios. After the screening, we found that the software can be applied to data whose hypocentral distance is less than 130 km and magnitude is larger than 3.5. The number of available events was reduced to 10, although the predicted magnitude scales are slightly overestimated.

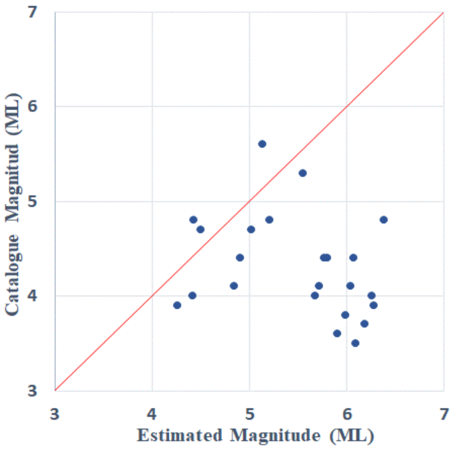

Figure 1. Comparison between the catalogued and estimated magnitude for the selected 24 events.

4.2. Hypocenter location estimation

The hypocenter estimation was computed with the software “hypo” developed by Dr. Takumi Hayashida, which uses the automatically picked P-wave arrivals to find reasonable hypocenter location that reduces the detected and predicted P-wave arrivals by repeated calculation. In general, the results show large differences between estimated and catalogue hypocenter locations as is shown in Figure 2, which were not reasonable due to the lack of stations along the coastal line for the case of subductions earthquakes.

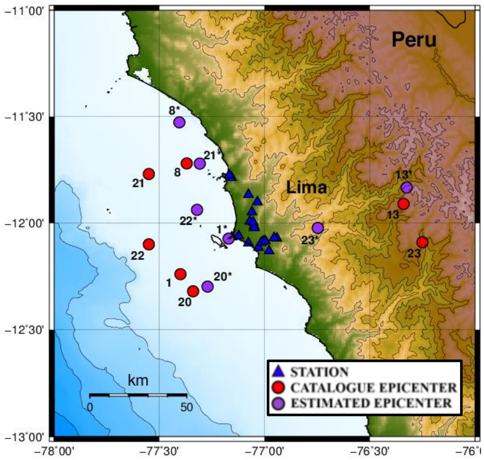

Figure 2. Map showing epicentral locations of the selected events (red circles: catalogue epicenters, purple circles: estimated epicenters).

4.3. Peak Ground Acceleration estimation

We obtained the observed PGAs from the dataset. We also applied the two GMPEs, considering soil conditions (Vs30 values) where the stations are located. We found that the agreement overestimated, underestimated and good correlations on the calculated values of PGA as is shown in Figure 3.

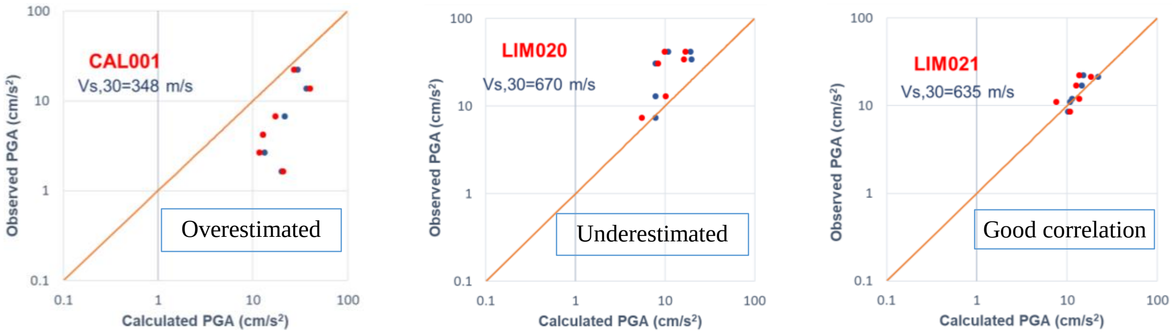

Figure 3. Comparison between the observed and predicted PGAs at three stations.

4.4. Analysis of the blind zone

Earthquake Early Warning Systems usually has a blind zone around the epicenter where the S-wave arrives ahead of or coincident with the warning issuance. The blind zone is defined as the region around the epicenter where no warning is issued because the strong shaking has already arrived by the time the alert is generated (Kuyuk and Allen, 2013).

Figure 4 shows the result of blind zone analysis for an event (date, time, magnitude, depth). Here we assumed that 3 seconds is required for the processing. For this earthquake P-wave front reached the farthest station 11.9 s after the

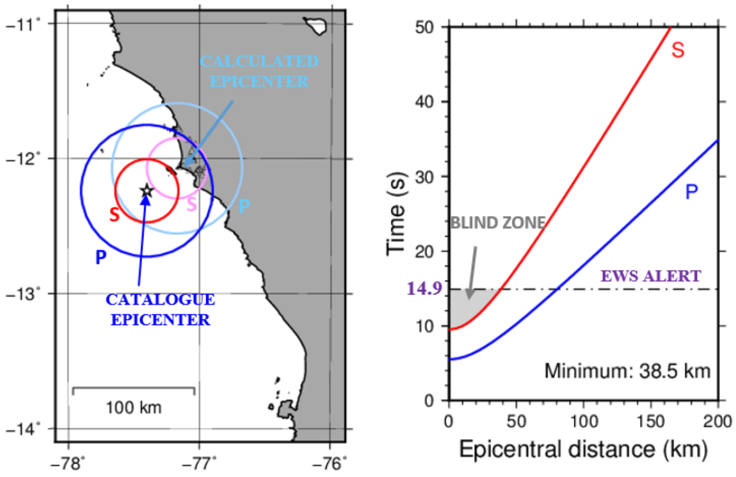

Figure 4. Left: Map of the calculated and catalogue (star) epicenter locations, along with P- and S-wave arrivals. Right: Time-distance plot illustrating the relative timing of arrivals of P and S waves, warning time and blind zone.

earthquake origin time and we found that at least 14.9 s is needed to determine magnitude and hypocenter location, and give a first alert to Lima (dashed black line). According to this result, the S-wave front arrives at a distance of 38.5 km at the warning time and Lima is outside of the blind zone. However, the result with the real-time estimated epicenter location indicates that the S-wave reaches all the stations at the warning time and this differs from the actual observations. This indicates that the estimated hypocenter is not reliable and accurate estimation of hypocentral location is important to prevent false alert and to find the affected area.

4.5. Experiment on determination of the epicentral distance using single stations

In this study, we also investigated the possibility to estimate epicentral locations using a single-station approach, since we have difficulty in accurate estimations of hypocenter location. Odaka et al. (2003) proposed a concept of estimation of epicentral distance and this is based on the analysis of the initial P-wave portion (2-3 s) observed at a single seismic station. In this method, the coefficient B is treated as an index to indicate the increasing ratio (i.e. slope of the envelope) of the P-wave. It can be obtained by fitting the envelope curve of absolute amplitude for the observed P-wave's initial phase into the following equation;

$$y(t) = Bt\exp(-At) \ , \tag{8}$$

where y represents envelope of high-frequency UD-component acceleration and t represents the time after P-wave onset. Parameter A is the regression coefficient that relates to earthquake size. After that, Yamamoto et al. (2012) proposed a method to improve the performance of the approach using the following approximation,

$$y(t) = Ct \ , \tag{9}$$

where coefficients C are derived by an ordinary least square regression. This method utilizes only 0.5 s window data of P-wave initial motion.

Here we tested the C-Δ method in this study to investigate if it can be a reasonable tool for the estimation of the epicentral distance also in Peru. For the procedure, we considered a 10-20 Hz bandpass filter and extracted 0.5 s of the P-wave onset for all earthquake recordings selected in this study. The relationship between the derived C value and the epicenter distance is shown in Figure 5. The number of data is limited and it is difficult to establish a reliable formula in Peru, but the derived trend is similar to those of Japan (Yamamoto et al., 2012).

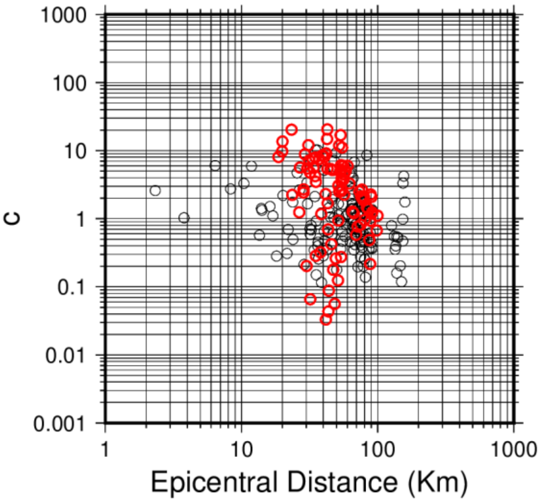

Figure 5. Relationship between C values and epicentral distance Δ for earthquakes presented in this study. Black circles represent the total data (24 earthquakes) and red circles represent the selected data (10 earthquakes).

5. CONCLUSIONS

In the hypocenter determination, we found that at least 8 stations are needed to estimate the hypocentral parameters. When the number of the seismic stations was larger than 16, the results were good and the hypocenter locations became very similar to those of the CISMID catalogue. On the other hand, when the number of the stations was between 9 and 12, the results were not reasonable, indicating that real-time observation stations should be distributed not only in Lima city, but also outside the city.

From the PGAs comparison, we noticed an overestimated tendency in the calculated values of PGA for stations with small Vs30 values (≤ 500 m/s). On the other hand, we also noticed an underestimated tendency in the calculated values of PGA for those stations with larger Vs30 values.

We found that the blind zone cannot be a big problem in the case of Lima but it is not feasible to install EWS in Peru at the present, because the hypocentral locations were not well determined under the present observation network.

Moreover, the determination of epicentral distance using single station can be used for the case of Peru, since we do not have enough seismic stations and it is used also for small earthquakes. We found a relationship between the C parameter and the epicentral distance of the earthquakes used for this study, and this information could help to implement the earthquake EWS of Peru in the future.

6. RECOMMENDATION

For the reasonable detection of subduction zone earthquakes, the stations should be located along the coastal line.

It is important to remember that the values of PGAs were calculated with GMPEs from other countries. Therefore, in order to increase the accuracy of the predictions the development of GMPE in the study area is recommended.

In order to increase the accuracy of the source-to-station distance, further accumulation of earthquake data including future earthquakes and past earthquakes are needed.

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