PREDICTION OF MAGNITUDE AND EPICENTRAL DISTANCE FROM A SINGLE SEISMIC RECORD

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ABSTRACT

Earthquake Early Warning System (EEWS) is issued by detection of P-wave, estimation of seismic parameters and decision to alarm. Earthquake magnitude and P-wave amplitude ($P_{max}$) are important parameters for EEWS, yet their dependence on source mechanism, focal depth and epicentral distance ($\Delta$) has not been fully studied. We examined a method to estimate an earthquake’s magnitude and epicentral distance using the initial part of P-wave data (within 3 s) for application in EEWS. The B-$\Delta$ method is used to estimate the epicentral distance from a single station data in a short time. Fitting a simple function with the form of $y(t) = Bt e^{-At}$ to the first few seconds of the waveform envelope, coefficients $A$ and $B$ are determined through the least-squares method. $LogB$ is inversely proportional to $log\Delta$. This relation holds true regardless of earthquake magnitude. $B$ values are calculated on the basis of 48 vertical-component accelerograms of the Ahar-Varzaghan earthquake in a magnitude range $M_n$ 4.5-6.4 and epicentral distances less than 100 km. Using this method, we could estimate the epicentral distance by $log\Delta = -0.69logB + 2.5$ and earthquake magnitude by $M_{eq} = 1.89logP_{max} - 1.76logB + 5.52 \pm 0.3$. The greatest advantage of this method is its accuracy and rapidness. The EEW issues several alarm messages during the course of one earthquake, improving the accuracy of the warning as the amount of available data increases. The EEW is transmitted to many kinds of devices and used for personal safety and automatic control.

Keywords: Earthquake Early Warning; B- $\Delta$ method; Single Station; NW-Iran.

1. INTRODUCTION

Sensitive seismographs, which greatly magnify ground motions, can detect strong earthquakes from sources anywhere in the world. The time, location, and magnitude of an earthquake can be determined from the data recorded by seismograph stations. Rapid estimation of the epicentral distance and magnitude is of fundamental importance for early earthquake detection and warning systems. Earthquake early warning systems (EEWS) use earthquake science and the technology of monitoring systems to alert devices and people when shaking waves generated by an earthquake are expected to arrive at their location. The seconds to minutes of advance warning can allow people and systems to take actions to protect life and property from destructive shaking.

P-wave warning is issued by the following steps: detection of P-wave, estimation of seismic parameters and decision to alarm (Yamamoto and Tomori 2013). Odaka et al. (2003) presented a novel method of estimating the magnitude and epicentral distance from a single seismic record in a few seconds after the P-wave arrival. This method is called the B- $\Delta$ method. They have found that the envelope waveform of the initial part of P-waves changes systematically with magnitude and epicentral distance. For example the Shinkansen EEWS in Japan, using this method rapidly estimates earthquake parameters from a single station data (Noda et al 2012). One of the systems that is now under practical use, called Urgent Earthquake Detection and Alarm System (UrEDAS), which has been used by railways network to stop trains in the event of an earthquake occurrence in Japan (Bito et al. 1986, Nakamura 1988). In the UrEDAS system, the magnitude is determined on the basis of the predominant period of P-waves, which may become longer with increasing magnitude. The pilot

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TDMMO (Tehran Disaster Mitigation and Management Organization) warning system is in its final stages for running experimental tests. The B-Δ algorithm has been used and the relation developed by Japan Meteorological Agency (JMA) is used for rapid estimation of magnitude and epicentral distance (Heidari 2016). Istanbul Earthquake Early Warning and Rapid Response System (IEEWRRS) have been deployed in 2002. In 2012, Istanbul Natural Gas Distribution Company (IGDAS) has started a project of “IGDAS Earthquake Risk Reduction System” collaboration with KOERI, Turkey. The main aim was to establish a real-time risk reduction system for the whole natural gas network (Zulfikar et al. 2014).

In this study, distance and magnitude are investigated rapidly from a single-station record of the Ahar-Varzaghan earthquakes, NW-Iran. Magnitude estimation is then readily performed on the basis of the P-wave maximum amplitude within a given short time interval after the P-wave arrival.

2. STUDY REGION

NW of Iran is exceptional within the Arabian-Eurasian continental collision zone. The tectonics is dominated by the NW-SE striking right-lateral North Tabriz Fault (NTF), which is a major seismogenic fault in this region. Historical seismicity in the northwest of Iran is mostly associated with this Fault (Fig. 1). Figure 1 presents an overview of northwestern Iran with topography, position of the Ahar-Varzeghan earthquake sequence, broadband stations and major faults as well as focal mechanisms for both largest mainshocks according to different international agencies. The last damaging earthquakes on the NTF occurred in 1721, rupturing the southeastern fault segment, and in 1780, rupturing the northwestern part. The understanding of the seismic behavior of this fault is critical for assessing the hazard in Tabriz, one of the major cities of Iran; the city suffered major damage in both the 1721 and 1780 events. North of the NTF seismicity is rare.

On August 11, 2012 the region was surprisingly struck by a shallow $M_w 6.4$ earthquake with pure right-lateral strike-slip character only about 50 km north of the NTF. It produced an east–west oriented surface rupture of about 12 km length (Faridi and Sartibi, 2012). Only 11 minutes later and about 6 km further NW a second event with $M_w 6.2$ occurred (Ghods et al. 2015; Zafarani et al. 2015). It showed an NE-SW oriented oblique thrust mechanism. The Ahar-Varzaghan doublet occurred in a region that has been characterized as having a low deformation rate and being bounded by deep-seated faults, among which the NTF is the most important (Hessami et al. 2003; Ghods et al. 2015; Donner et al. 2015). Such a characterization is consistent with the seismic record, until 2012. This earthquake sequence provides an opportunity to better understand the processes of active deformation and their causes in the NW Iran.

3. METHODOLOGY

Envelope waveforms of seismic waves can differ depending on earthquake magnitude, focal depth, and epicentral distance; ground motion can be displayed on a logarithmic scale to determine these differences visually (Odaka et al. 2003). The noise levels (the small-amplitude initial portion of the P-phase) preceding the arrival of the P-wave, and the large amplitude later phases (i.e. the S-phase) can then be recognized easily and the differences in waveform characteristics immediately understood (Fig. 2). Logarithmic waveforms have shown that the initial parts of seismic waves (within several seconds after arrival of the P-wave) vary systematically in form in response to earthquake magnitude and epicentral distance. The following function can be used to quantitatively evaluate differences in waveform:

$$y(t) = Bt \exp(-At)$$

Here $y(t)$ is the envelope waveform constructed from the observed seismic waveform, the origin of time $t$ is taken at P-wave arrival time. First, a nonnegative waveform is constructed by taking absolute values of the original waveform. Second, the envelope waveform $y(t)$ is constructed. Figure 2 shows an example which the envelope was simply constructed by taking the maximum amplitude (for 0.1 s).
Figure 1: Overview of seismicity of NW-Iran (Donner et al. 2015). The star marks the position of the Ahar-Varzaghan earthquake. NTF, North Tabriz fault; NAF, North Anatolian fault; EAF, East Anatolian fault. Arrows give Global Positioning System velocities (Djamour et al. 2011). Black triangles mark broadband stations of the Iranian National Seismic Network and the Turkish National Broadband Network. Black inverted triangles mark short- period stations of the Iranian Seismic Telemetry Network. Reversed triangles, Iranian Seismological Center [IRSC]; diamonds, Kandilli Observatory and Earthquake Research Institute [KOERI]; circle, Incorporated Research Institutions for Seismology [IRIS]; rectangles, Building and Housing Research Center [BHRC]. Inset shows the mechanisms for both mainshocks according to international agencies: Global Centroid Moment Tensor Project (Global CMT), U.S. Geological Survey (USGS), GEOFON Global Seismic Network (GFZ).

The unknown parameters $A$ and $B$ are determined using least-squares method (Fig. 2). Using a fitting curve in the form of $y(t)=Bt.e^{-At}$ has the effect of applying low-pass filtering (smoothing) to waveform data. This method is not affected by contamination due to high-frequency noise (Odaka et al. 2003, Noda et al. 2012). The parameter $B$ defines the slope of the initial parts of the P-waves, and $A$ is related to amplitude variation over time. Figure 2 (a) shows a vertical-component accelerogram recorded from the first Ahar-Varzaghan earthquake ($M_w$ 6.2) and (b) detection of the P-wave. P-wave start time should be very accurate to avoid any mistakes in evaluation of $A$ and $B$ values. Also, figure 2 (c) shows logarithm of absolute values for the selected waveform with epicentral distance of 24 km in the NW-Iran (Rec. No. 5520-1). The continuous line on figure 2 (c) indicates the fitting of function $Bt.e^{-At}$ to an envelope of amplitudes. The initial low-amplitude part of seismogram denotes the noise and the slope rising sharply from the noise level indicates the P-wave arrival.

Figure 3 shows the relationship between epicentral distance and the coefficient $B$. $B$ values are calculated on the basis of 48 vertical-component accelerograms of the Ahar-Varzaghan earthquake sequence with magnitude range $M_w$ 4.5-6.2, recorded by the BHRC (Building and Housing Research Center). The data length used in the analysis was 3 s after start of P-wave. It is clear from Figure 3 that $\log B$ is linearly proportional to $-\log \Delta$, where $\Delta$ denotes the epicentral distance. Note that this relation seems to be independent of earthquake magnitude (Odaka et al. 2003). The dispersion of data is not large and this result is important because a regression line can be obtained, via the least-squares method, as a relation between $\log B$ and $\log \Delta$, and this regression line can be used to estimate an epicentral distance from the value of $B$. The epicentral distance can be estimated immediately after arrival of the P-wave by determining the empirical relationship between the coefficient $B$ and epicentral distance.
Figure 2. (a) Vertical-component accelerogram recorded Mw 6.2 and (b) detection of the P-wave and (c) logarithm of absolute values for the selected waveform. The continuous line indicates the fitting of function $y(t) = Bt \exp(-At)$ to an envelope of amplitudes.
If early earthquake warnings are to be effective, earthquake size must be evaluated quickly. Earthquake magnitude could be estimated by means of the following formula (Odaka et al. 2003):

\[ M_{est} = a \log P_{max} + b \log B + c \]  \hspace{1cm} (2)

where \( M_{est} \) represents the estimated magnitude and \( P_{max} \) the maximum amplitude of P-wave within any specified short time interval (e.g., 3 s) after arrival of the P-wave. The constants \( a \), \( b \), and \( c \) in Equation 2 can be determined empirically.

4. RESULT AND DISCUSSION

With the mentioned method, the time required for estimating the distance to the epicenter is quite short. In the present study, there was a good linear relationship between logB and log\( \Delta \), as can be seen in Figure 2. The best fitted line is obtained using the least-squares method. The relation for the 3 s time window for the Ahar-Varzaghan region, NW-Iran is as follow:

\[ \log \Delta = -0.69 \log B + 2.5 \pm 0.4 \]  \hspace{1cm} (3)

Earthquake magnitude obtained as a function of maximum phase amplitude received during the initial seconds and epicentral distance. In the current study, earthquake magnitude estimated by the following equation:

\[ M_{est} = 1.89 \log P_{max} - 1.76 \log B + 5.52 \pm 0.3 \]  \hspace{1cm} (4)

In Figure 4, we show an example of waveforms that vary in form with epicentral distance. Graphs are for two stations with epicentral distances 107 and 18 km of the Ahar-Varzaghan earthquake \( M_w 6.2 \) on 11 August 2012. The initial low-amplitude part of each seismogram denotes the noise and the slope rising sharply or gradually from the noise level indicates the P-wave arrival. Comparison of two graphs shows that the rising envelop slope becomes gentle with increasing epicentral distance. The slop of waveform envelop in 18 km is sharper than the other.

Odaka et al. (2003) described the amplitude of the large earthquake increases gradually with time, whereas that of the small earthquake decreases soon after the P-wave arrival, which is consistent with the observation by other researchers (Noda et al. 2012). Figure 5 shows a near field record which S-waves arrive in time of less than 3 s. It may be impossible to estimate the magnitudes and distances of very local earthquakes in 3 s of initial part of P-wave. In this conditions time window intervals can set to 2 s and errors will increase.
We have compared the Mest and Mobs values to test the reliability of the magnitude estimation (Figure 6, Top). It is clear that differences between predicted and observed values are almost insignificant. Furthermore, comparison between observed and estimated magnitude with epicentral distance is shown in figure 6. Estimated values for records with epicentral distance more than 70 km are lesser than observed values. Attenuation of seismic wave in the active region of Iran (tectonically active zones characterized by a high degree of heterogeneity) is high and it can be the reason of underestimation of the magnitude (Mahood, 2014).

It would be more appropriate to compare with other active regions in order to observe whether characteristics are present in the study area. As a result of tectonic differences in active regions, such linear relations have a different slope relative to the relation applied in the other region and consequently each active seismic region needs a specific relation. Figure 6 shows the comparison of this study with relationships developed for the Tehran region and Japan. The obtained relationship is generally similar to the relation developed for the Tehran region (Heidari 2016).

Noda et al. (2012) obtained new B-Δ relation and presented new methods to improve the performance of epicenter estimation by introducing variable time windows, instead of the conventional fixed time window for Japan. Odaka et al. (2003) from the results of their earlier numerical experiment, recommend 2 or 3 s for time window. They mentioned that it may be difficult to estimate the magnitudes of large earthquakes (e.g., M8 earthquakes) within such a short time after arrival of the P-wave because the duration time of the rupture is far longer than 2 to 3 s. This problem is addressed by calculating magnitudes repeatedly with lapses of time and time window intervals can set to 2 or 3, and so forth. When amplitudes of P-waves increase with time, estimated magnitudes may also become large. Odaka et al. (2003) expected that $A$ parameter may be useful for distinguishing shallow and deep earthquakes and large or small earthquakes.
Figure 6. Comparison between different tectonic regions: this study, Tehran area (Heidari 2016) and Japan (Okada et al. 2003).

5. CONCLUSIONS

The effectiveness of earthquake early warning systems (EEWS) to mitigate earthquake hazards and reduce casualties from earthquakes, especially major ones, has been demonstrated in this article. The B-Δ method can apply as a new stand-alone seismographic system that detects an earthquake and issues a warning immediately after the arrival of the P-wave. The epicentral distance is estimated from the coefficient \( B \) which is determined by fitting the equation \( y = B e^{\Delta t} \) to the vertical component envelop of the accelerograms of the initial P-wave. Coefficient \( B \) is almost independent of magnitude, which is mainly affected by epicentral distance. Moreover, to develop magnitude-scaling relation for earthquakes, \( P_{\text{max}} \) parameter within the initial 3 s of P-wave arrival is used. In the current study, earthquake magnitude is estimated by using an empirical magnitude–amplitude relation that includes the epicentral distance as an input parameter.

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7. REFERENCES


