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Rapid Estimating Epicentral Distance and Magnitude from a Single Seismic Record of Sarpol-e Zahab Earthquake

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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. The EEWS provides advance warning of estimated seismic intensities and expected arrival time of S-waves. These estimates are based on prompt analysis of hypocenter location and earthquake magnitude using data observed by seismographs near the epicenter. In this study, the B-Δ method is examined to estimate an earthquake's magnitude and epicentral distance using only initial part of P-wave data (3 s) from a single station for application in EEWS. Fitting a simple function with the form of $f(t)=Bt\times \exp(-At)$ to the first few seconds of the waveform envelope, coefficients A and B are determined through the least-squares method. B decreases with distance and shows independence from magnitude and logB is inversely proportional to logΔ, where Δ is the epicentral distance. B values are calculated on the basis of 65 vertical-component accelerograms of Sarpol-e Zahab earthquake (M_w 7.3) with epicentral distances less than 100 km. The magnitude and an amplitude parameter Pmax determined from the very beginning of P-wave, are important for EEWS, yet their dependence on source mechanism, focal depth and epicentral distance has not been fully studied. Using this method, we could estimate the epicentral distance by $\log\Delta = -0.57\log B + 2.4 \pm 0.4$ and earthquake magnitude by $M_{est} = 1.99 \log P_{max} - 1.76 \log B + 5.62 \pm 0.3$. The greatest advantage of this method is its accuracy and rapidness. The EEW system 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. It is very important to observe strong motion in real-time using a dense network in order to improve the EEW system.

Keywords:
Earthquake early warning systems; B-Δ method; Single station, Sarpol-e Zahab

1. Introduction

The Earthquake Early Warning (EEW) system provides advance warning of estimated seismic intensities and expected arrival time of S-waves. These estimates are based on prompt analysis of hypocenter location and earthquake magnitude using data observed by seismographs near the epicenter. The system issues several EEW messages during the course of one earthquake, improving the accuracy of the warning as the amount of available data increases.

Real-Time Earthquake Information System can be used to determine earthquake parameters and then transmit these results to the center in order to issue an EEW. The practical service of EEW in Japan has been in operation since Oct. 2007 [1]. At the moment, a new strategy for a P-wave based, on-site earthquake early warning system has been developed and tested on Japanese strong motion data. The key elements are the real-time, continuous measurement of the peak amplitude parameters and their empirical combination to predict the ensuing peak ground motion. The observed parameters are compared to threshold values and converted into a single, dimensionless variable. A local alert level is issued as soon as the empirical combination exceeds a given threshold. The following modules are indispensable to accurately estimate earthquake parameters and generate warnings, based on limited signals, in a timely manner. These modules include the transmission of real-time monitoring data, real-time phase picking and event detection, real-time earthquake location, estimation of magnitude, prediction of seismic intensity, and evaluation of affected area and release of warning information [2-4]. Problems of the present EEWS are: (1) Sometimes EEW is issued after S-wave arrival, because warning times become negative within an area about 30 km (Blind Zone) from the epicenter. Blind Zone or the negative warning area is within a few km from the epicenter, where S-wave and/or strong shaking has already reached; (2) Underestimation of seismic intensity during a massive earthquake: In the 2011 Tohoku-Oki earthquake (M9), the EEW was issued to the area close to the hypocenter earlier than the S-wave arrival. However, the EEW cannot be issued to areas further away from the hypocenter, where the observed seismic intensity is greater than 5-lower; (3) False alarm: Earthquakes sometimes occurred simultaneously over the entire fault region, such that the EEW system became confused, and did not always determine the hypocenter location and earthquake magnitude correctly.

Odaka et al. [5] have developed a new type of earthquake early detection and warning system on the basis of the initial part of the P-wave. They presented a novel method of estimating the magnitude and epicentral distance from a single seismic record in a short amount of time. This method is called B-Δ method. They found that the initial rising slopes of the P-wave envelope waveform of vertical ground acceleration were inversely proportional to the epicentral distances of earthquakes. This linear relation was confirmed for the seismic wave data of different earthquake catalogs, and they found that the relation held true regardless of the earthquake magnitudes and depths though the scatter of plotted data was somewhat large [1, 5]. By using this relation, the epicentral distance nearly immediately after the P-wave arrival can roughly be estimated. The magnitude estimation is possible from the maximum amplitude observed within a given short time interval after the P-wave arrival.

A close investigation was made about the P-wave initial slope by using the wave data for the latest large earthquake, Sarpol-e Zahab Earthquake in west of Iran (Figure 1), in order to establish decisively the relationship between the slope and the epicentral distance. Magnitude estimation is then readily performed on the basis of the P-wave

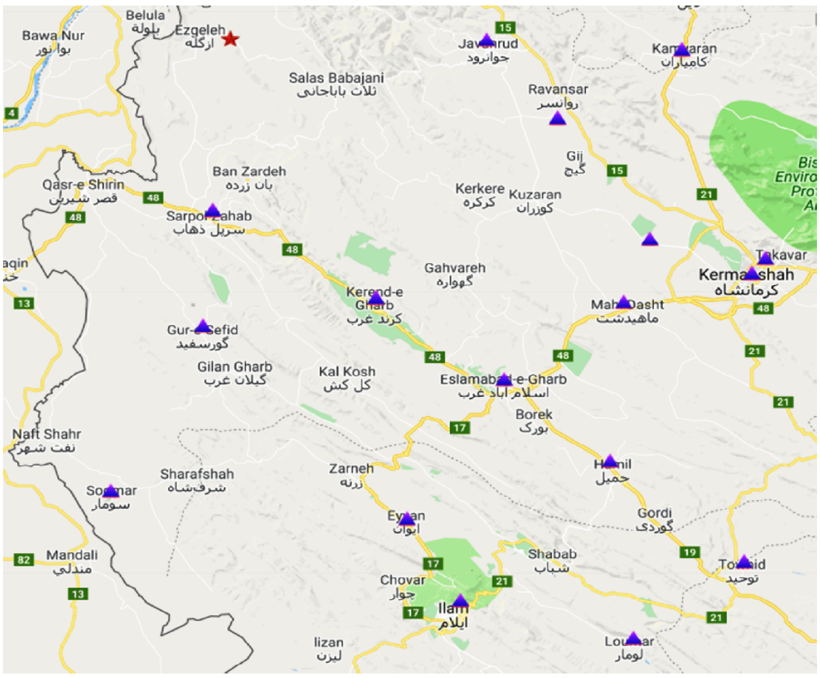

Figure 1. The red star marks the position of the Sarpol-e Zahab earthquake (M_w 7.3 on November 12, 2017). Triangles: Iran Strong Motion Network of BHRC.

maximum amplitude within a given short time interval after the P-wave arrival.

2. Estimation of Magnitude and Epicentral Distance

Envelope 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 [5]. The noise levels (the small-amplitude initial portion of the P-phase) preceding the arrival of 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 (Figure 2).

The P-wave initial slope (the rate of increase in

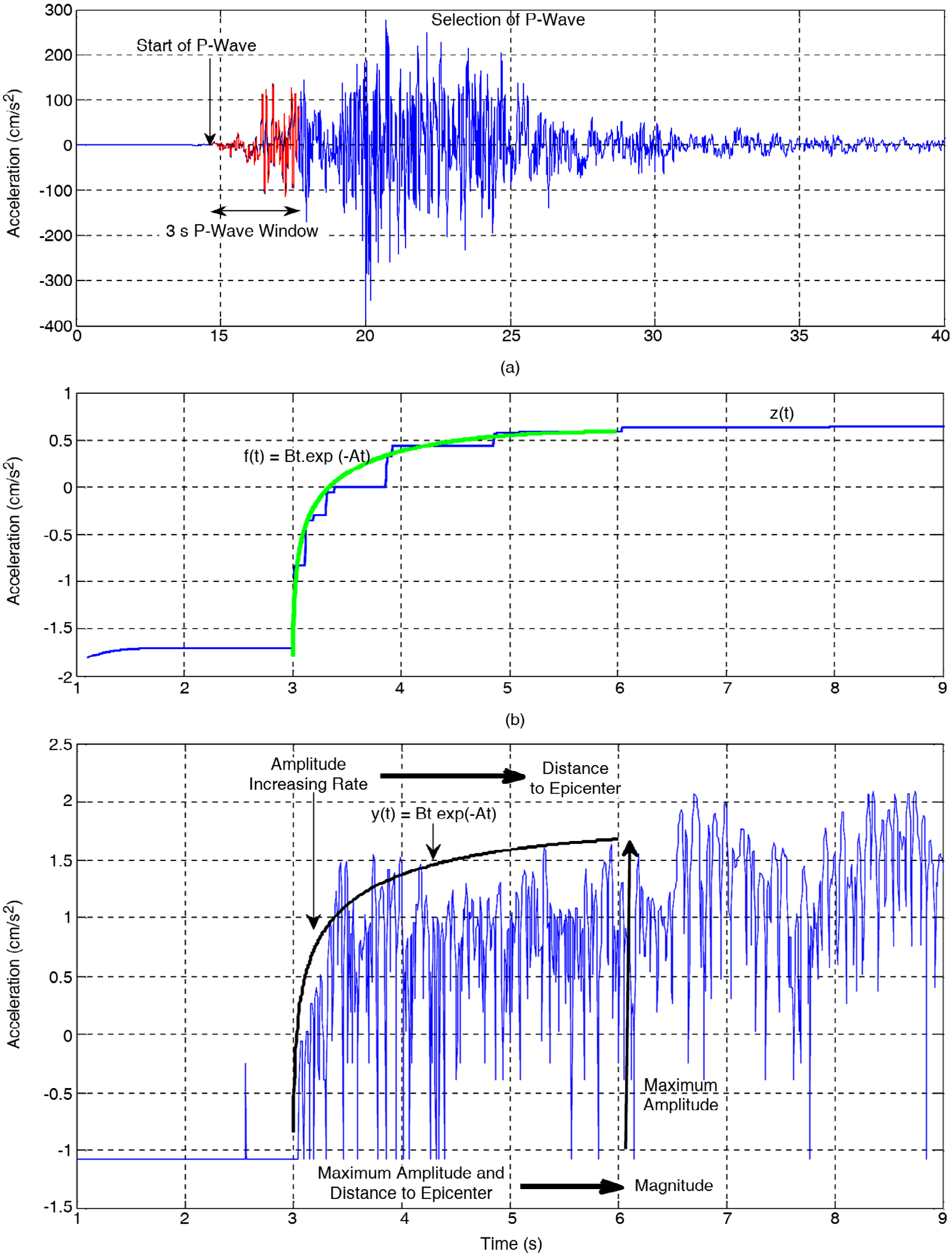

Figure 2. (a) Vertical-component accelerogram recorded M_w 7.3, (b) The envelope $z(t)$ and $f(t)$ and (c) logarithm of absolute values for the selected waveform. The continuous line indicates the fitting of function $y(t) = Bt \times exp(-At)$ to an envelope of amplitudes.

amplitude of P-wave in its very beginning) is evaluated as follows. First, a non-negative waveform $y(t)$ is made by taking absolute values of original waveform $x(t)$. Next, the envelope waveform $z(t)$ of $y(t)$ is constructed. The envelope $z(t)$ is, in the present study, simply constructed by retaining the previous maximum amplitude (that is, $z(t)$ = max of $y(s)$, where $0 < s \leq t$) at every sampling time t. Then it is tried to fit the following function $f(t)$ to the envelope $z(t)$ (Figure 2).

$$f\left(t\right) = Bt \times exp\left(-At\right) \quad (1)$$

The origin of time t is taken at P-wave arrival time. The unknown parameters A and B are determined in terms of the least-squares method by taking the logarithm of Equation (1). To avoid minus infinity (log 0) in the computation, a small value is added to the zero acceleration. The parameter B defines the slope of the initial part of the P-wave envelope and the parameter A represents a long-period amplitude variation with time. When A is positive, $B/(Ae)$ gives the maximum amplitude where e means the base of natural logarithm. This case is typical of small earthquakes, indicating that the initial amplitude increases sharply and decays quickly soon after the P-wave arrival. When A is negative, the amplitude increases exponentially with time. This is a characteristic of large earthquakes [6].

Figure (2) shows an example in which the envelope was simply constructed by taking the maximum amplitude (e.g. for a 0.1 s time window). Using a fitting curve in the form of $Bt \times exp(-At)$ has the effect of applying low-pass filtering (smoothing) to waveform data. This method is not affected by contamination due to the high-frequency noise [1, 5]. Figure (2a) shows a vertical-component accelerogram recorded from the Sarpol-e Zahab earthquake (M_w7.3) and detection of the P-wave. P-wave start time should be measured very accurately to avoid any mistakes in evaluation of A and B values. Besides, Figure (2b) shows envelope $z(t)$, constructed by retaining the previous maximum amplitude and $f(t)$. Figure (2c) shows the logarithm of absolute values for the selected waveform with epicentral distance of 39 km in Sarpol-e Zahab station (Rec. No. 7384-1). The continuous line on Figure (2c) indicates the fitting of function $Bt \times exp(-At)$ 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.

This paper aims to establish the linear relation between the initial rising slopes of the P-wave envelope waveform and the epicentral distances of earthquakes that was found by [5]. Figure (3) shows the relationship between epicentral distance (Δ) and the coefficient B. It is clear that B values decrease almost linearly with increasing Δ over the wide range of distance. They look to be independent of the magnitude and focal depth [5]. We can obtain a regression line for the relationship between log$B$ and logΔ from this data set by the least-squares method, and this regression line can be used to estimate an epicentral distance from the value of B. Once a value of B is evaluated from observed wave motion, we can immediately estimate an epicentral distance via this B-Δ relation. Judging from the scatter of the data in the figure, it can be expected that an estimated distance may roughly lie in the range between half and twice the correct distance. This accuracy may be acceptable when it is considered that the estimation is performed within a quite short time, say, 3 seconds, after the P-wave arrival. The azimuth of the epicenter, as seen from an observation station, can be inferred from the ratio of two horizontal-component P-wave first motions and the polarity of a vertical-component

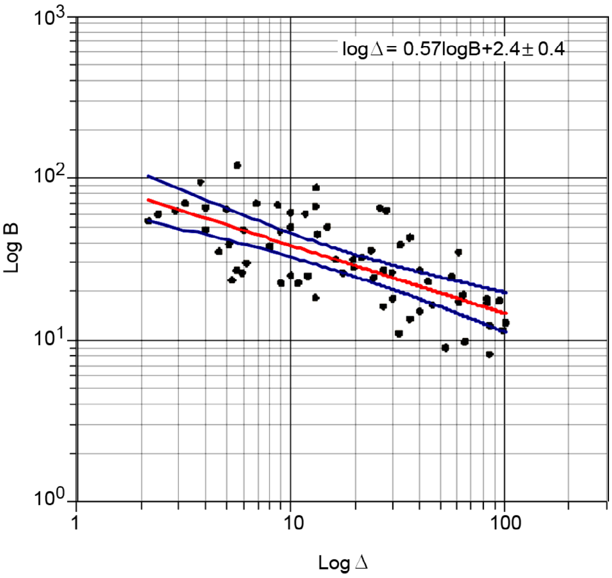

Figure 3. Relationship between coefficient B (initial slope of envelope of P-waves) and epicentral distance Δ with 95% confidence interval.

P-wave motion [1, 5, 7]. The location of the epicenter can then be estimated by P-wave recognition and epicentral azimuth estimation using three components of the single station.

B values are calculated on the basis of 65 vertical-component accelerograms of the Sarpol-e Zahab earthquake sequence with magnitude range M_w 4.5-7.3, recorded by the BHRC (Building and Housing Research Center). The data length used in the analysis was 3 s after the start of P-wave.

As mentioned, the epicentral distance can be estimated immediately after arrival of the P-wave by determining the empirical relationship between the coefficient B and Δ. If early earthquake warnings are to be effective, earthquake size must be evaluated quickly. Earthquake magnitude could be estimated by means of Equation (2) [5]:

$$M_{est} = a\log P_{\max} + b\log B + c \quad (2)$$

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.

3. Results 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 $\log B$ and $\log \Delta$, as seen in Figure (3). The best fitted line is obtained using the least-squares method. The relation for the 3 s time window for the Kermanshah region is as follows:

$$\log \Delta = -0.57\log B + 2.4 \pm 0.4 \quad (3)$$

The decrease in the P-wave initial slope B with distance may be caused by the scattering, attenuation and geometrical spreading of seismic waves during propagation. Tsukada et al. [8] made the numerical experiments on the waveform change with distance based on the scattering theory. The vertical spread of B values of respective earthquakes may be mainly caused by the difference in the nature of the wave scattering and attenuation (that is, the difference in the underground structure) along each ray path connecting the source and station. On the other hand, if we find any earthquake whose B values deviate systematically from the standard B-Δ relation, then we can expect that the origin of the deviation (anomalous distribution) may primarily lie in its source process. The time variation of the stress drop during the fault generation may be a substantial factor that affects the P-wave initial slope (rate of the increase in amplitude). Theoretically speaking, indeed, the P-wave amplitude (waveform) varies depending upon its time history [6].

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 Equation (4):

$$M_{est} = 1.99\log P_{max} - 1.76\log B + 5.62 \pm 0.3 \quad (4)$$

We considered V_p = 6.5 km/s and V_s = 3.5 km/s. For Sarpol-e Zahab station (Δ = 39 km) P-time is 6 s and calculation time is 4 s. We need 10 s for warning time whereas S arrival time is 11.2 s, then we have only 1.2 s time for the decision to alarm. Blind Zone, an area where S-wave and/or strong shaking has already reached, is ~35 km from the epicenter at this time. For the stations near the epicenter, we will have more time to alarm and therefore small blind zone. For very near stations, there is not enough time to record 3 s initial part of P-wave and S-waves arrive before 3 s.

Figure (4) shows an example of waveforms that vary in form with epicentral distance. Graphs are for two stations with epicentral distances 161 km (Loomar station) and 39 km (Sarpol-e Zahab station) of the Sarpol-e Zahab earthquake M_w 7.3 on November 12, 2017 (Figure 1). 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. We can recognize that the fitting curves well represent the respective envelope waveforms. It is clear that the initial rising slopes of the P-waves of the both records are entirely different. Comparison of two graphs shows that the rising envelop slope becomes gentle with increasing epicentral distance. The slope of waveform envelop in 39 km is sharper than the other.

Odaka et al. [5] 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

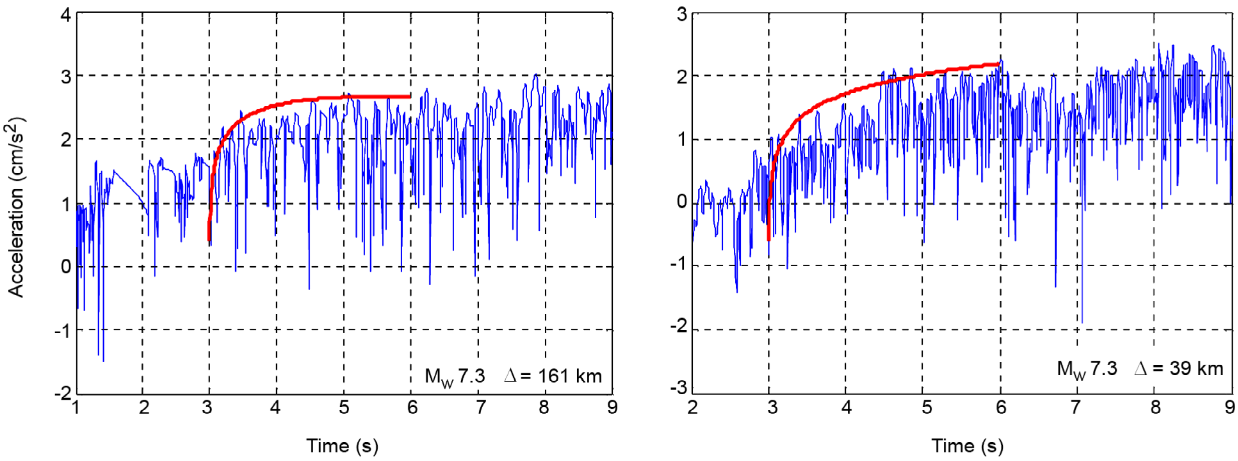

Figure 4. Comparison between two waveforms that vary in form with epicentral distance of the Sarpol-e Zahab earthquake M_w 7.3. Light curves are the fitting curves of the form *Bt* x *exp* (-*At*).

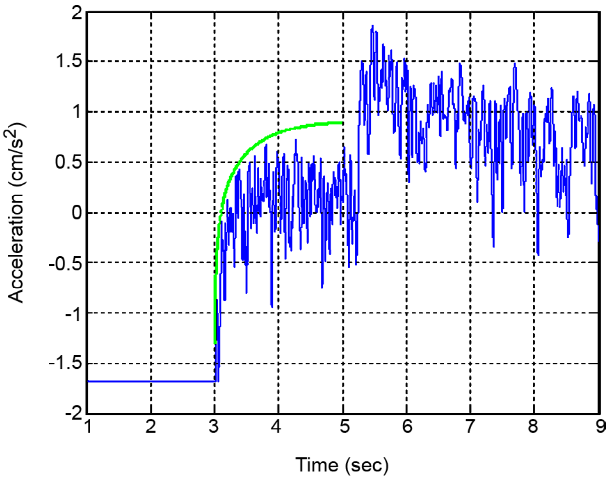

Figure 5. Vertical-component accelerogram recorded M_w 5.2 and Δ = 15 km.

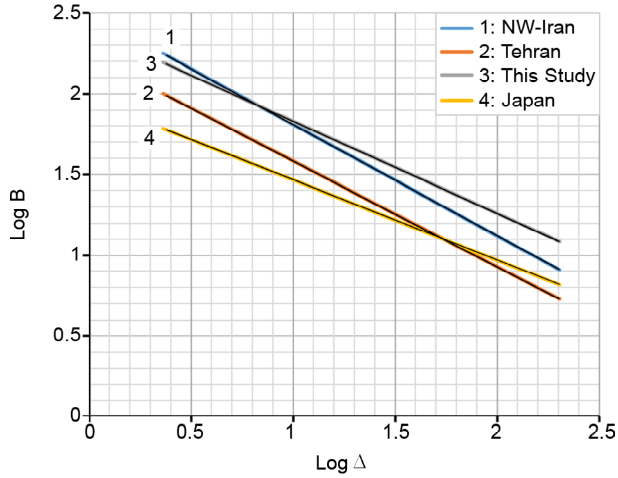

Figure 6. Comparison between different tectonic regions: NW-Iran [9], Tehran area [10], this study and Japan [5].

with the observation by other researchers [1]. Figure (5) shows a near-field record in 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.

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 NW-Iran, Tehran region and Japan. The obtained relationship is generally similar to the relation developed for NW-Iran [9].

Noda et al. [1]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. As Odaka et al. [5] mentioned in their paper, the time window width of 3 s is too long for a *M*4 or smaller class of earthquakes because the duration of the P-pulses of these class earthquakes may be far shorter than that. They, from the results of the 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., *M*8 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. [5] expected that A parameter may be useful for distinguishing shallow and deep earthquakes and large or small earthquakes. The greatest advantage of this method is its accuracy and rapidness and it can be used for all faulting mechanisms.

4. Conclusion

This study used a practical method to improve the performance in estimation of the magnitude and epicentral distance. This 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 that is determined by fitting the equation $f(t) = Bt \times exp(-At)$ to the vertical component envelop of the accelerograms of the initial P-wave. It is found that the rising slope of the initial part of the P-wave envelope waveform decreases almost linearly with increasing epicentral distance over the wide range of distance and that this linear relation looks to be independent of the earthquake magnitude and focal depth. Moreover, to develop magnitude-scaling relation for earthquakes, Pmax 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. We could estimate the epicentral distance by $\log\Delta = -0.57\log B + 2.4 \pm 0.4$ and earthquake magnitude by $M_{est} = 1.99\log P_{\max} - 1.76\log B + 5.62 \pm 0.3$. Blind Zone, an area where S-wave and/or strong shaking has already reached, is ~35 km from the epicenter at this time. The greatest advantage of this method is its accuracy and rapidness. The proposed methodology provides a more reliable prediction of the expected ground shaking and improves the robustness of a single-station, threshold-based earthquake early warning system.

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