New Magnitude Scaling Relation and Algorithm for Earthquake Early Warning in Tehran

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ABSTRACT

Tehran, the capital of Iran, is located in the southern part of Alborz mountains in north of Iran, which is an earthquake prone area. The recent developments in Earthquake Early Warning Systems (EEWS) encourage its application for seismic hazard mitigation, especially in mega-cities like Tehran. An effort was made here to develop the necessary relations and an algorithm for EEWS based on the initial few seconds of the P-wave arrival. For this purpose, a total of 654 accelerograms recorded by Road, Housing and Urban Development Research Center (BHRC) in Alborz region with the magnitude (Mw) range of 4.8 to 6.5 in a period of 1995 to 2013 was employed. Among several parameters conventionally used for EEWS, the average ground motion period (τ_c), peak displacement (P_d) and their multiplications ($\tau_c \times P_d$) in a three-second time window from the beginning of an earthquake record were used to introduce the new magnitude scaling relations for Alborz region. The robust correlation between the estimated τ_c, P_d, and $\tau_c \times P_d$ with the magnitude were used to validate their accuracy and application for EEWS. Furthermore, the P_d value of 0.3 (cm) and $\tau_c \times P_d$ value of 1 were found to be the good indicators to separate earthquakes into non-destructive and destructive. The developed relations were also compared with those given by Wu and Kanamori (2008), and Heidari et al. (2013). The comparisons show good agreements with the Wu and Kanamori's relations, and differ with the one given by Heidari et al. This difference was attributed to the employed data by Heidari et al., which were limited to the magnitudes lower than 4.6. Finally, the outcomes were used to present a new algorithm for EEWS in Alborz region.

Keywords:
Earthquake early warning; Magnitude estimation; Alborz region; Average period; Peak displacement

1. Introduction

Concurrent with the development of urbanization, earthquake hazards pose serious threats to lives and property in urban areas. For seismic hazard mitigation, a practical earthquake forecast method appears to be far from realization, because of the extreme complexity involved in earthquake processes [1]. Meanwhile, an alternative approach to mitigate seismic hazards is the development of earthquake early warning systems (EEWS) [2-5]. An EEWS provides a few seconds to tens of seconds of warning time for impending ground motions, allowing for mitigation measures in the short term.

Considering the advent of the digital data logging and transmission, the implementation and use of

EEWS as an effective earthquake risk reduction strategy is more encouraged in high seismic hazard countries like Japan and USA [6]. Iran is one of the seismically active regions of the world in which many active faults are located. These circumstances, along with the concentration of population in Tehran mega-city, emphasize the importance of early warning system implementation to reduce losses caused by the earthquakes.

There are two main approaches in estimating earthquake parameters using P-wave arrival, which are based on frequency content and amplitude of the initial few seconds of P-wave arrivals [6]. Nakamura first used the frequency content of the initial few seconds of P-wave arrivals. He suggested that larger events cause initial ground motion with longer periods than smaller events [4]. Based on this outcome, the researchers used two important parameters to estimate the magnitude of an earthquake in early stages of rupture. The first parameter is dominant ground motion period (τ_P^{max}) [3, 7], and the second is average ground motion period (τ_c) [5, 8, 9, 10]. Recently, new methods such as artificial neural networks [11], virtual seismologist [12-13] and slip-weakening distance of near-fault records [14] have also been developed for such purposes.

Heidari et al. [15-16] made an effort to estimate magnitude scaling relation using τ_c method for Tehran city. Their employed database was limited to the earthquake data in Tehran region, which experienced the earthquakes with magnitudes lower than 4.6. They tried to overcome this main obstacle by combining the large magnitudes data from other countries such as USA, Japan and Taiwan with those of low magnitude ones in Tehran region. Meanwhile, this may not be an ideal approach due to the special seismogenic features and seismicity of Alborz region, which is even different with the other seismotectonic zones in Iran such as Zagros or Kopet Dagh seismotectonic zones [17]. Seismic activity in Iran is not uniform due to its complicated tectonic nature. The highly seismogenic zones of Alborz and Kopet Dagh, extending along the northern borders of Iran and Afghanistan, constitute a part of the northern limit of the Alpine-Himalayan orogenic belt. These zones make contact with the stable Turan platform (Eurasia) to the north [18-19].

In this study, an attempt is made to overcome this deficiency by employing the data not only in the Tehran region but also in whole Alborz region, which experienced the earthquakes with the magnitudes in the range of 4.5 to 6.5. To this end, the acceleration data recorded by Road, Housing and Urban Development Research Center (BHRC) in Alborz area is used here [20]. These data are collected among 81 BHRC stations with the magnitudes in the range of 4.8 to 6.5, and the distances in the range of 6 to 90 km (Figure 1) in a period of 1995 to 2013. The τ_c, P_d, and $\tau_c \times P_d$ parameters are estimated from the displacement records calculated using vertical accelerograms. Then, their relations with the magnitude are examined. Since the estimated τ_c, P_d, and $\tau_c \times P_d$ parameters from waveforms at individual stations exhibit large variability (probably due to noise, site and path effects) [7], the mean τ_c, P_d, and $\tau_c \times P_d$ observations at different sites for each event is used in deriving magnitude scaling relations for the parameters. To show the accuracy and applicability of the developed relation in EEWS implications, they are compared with those given in national and international scales. Furthermore, two threshold values for P_d, and $\tau_c \times P_d$ parameters are defined to separate between non-damaging and damaging earthquakes. At the end, these outcomes are combined to introduce a new efficient EEW algorithm in Alborz region.

2. Magnitude Estimation Based on τ_c and P_d Methods

The τ_c method was first introduced by Kanamori [8], which is a modified version of the method originally developed by Nakamura [4]. The period parameter is calculated from the first several seconds of P-wave data. To this end, first, the parameter r should be computed as follows:

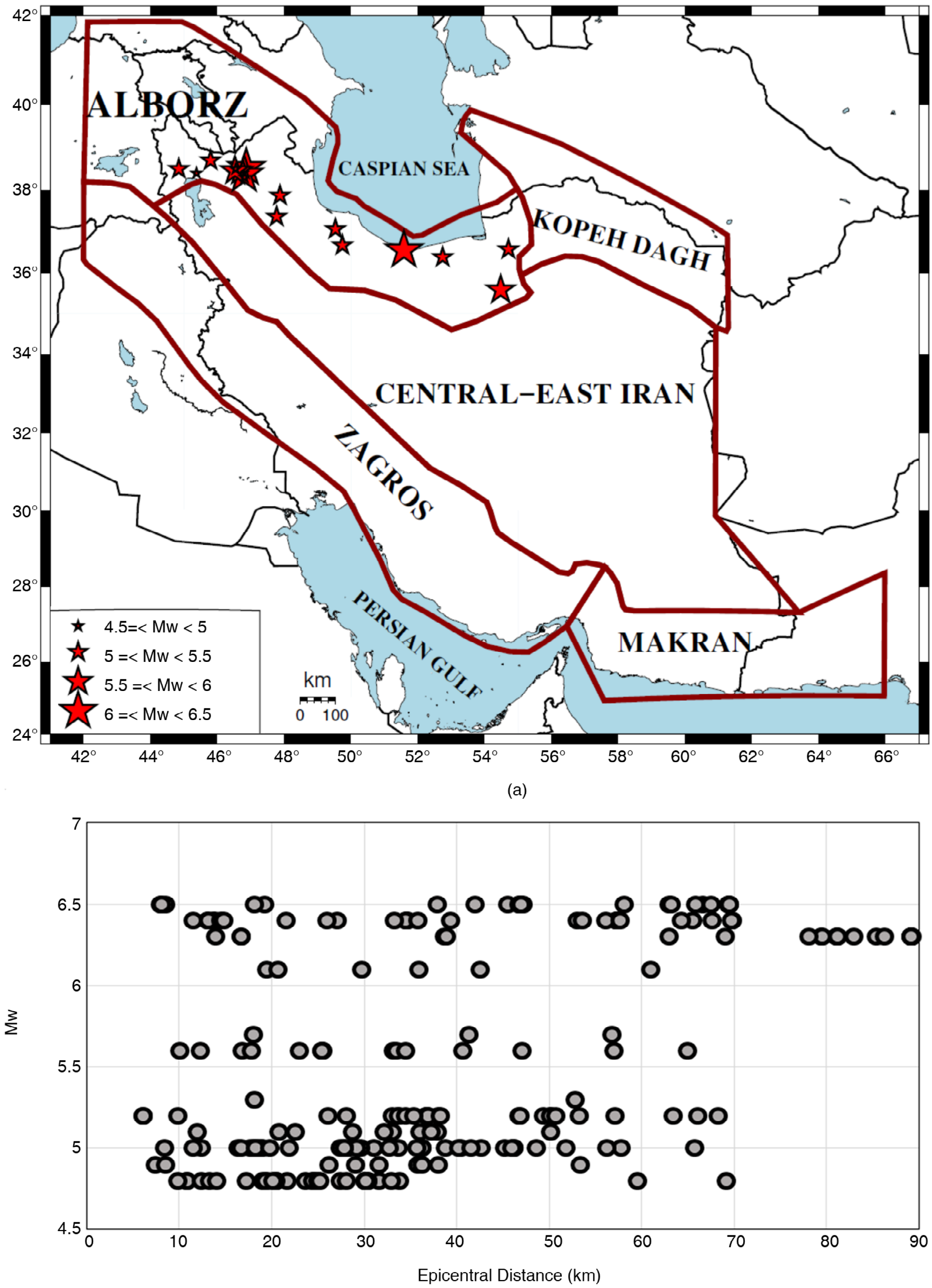
$$r = \frac{\int_0^{t_0} \dot{u}^2(t)\,dt}{\int_0^{t_0} u^2(t)\,dt} \tag{1}$$

where $u(t)$ and $\dot{u}(t)$ are displacement and velocity ground motions, respectively. The integration is over the time interval (0, t_0) after the onset of the P-wave and t_0 is set at 3 seconds. Using Parseval's theorem,

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

where f is the frequency, $\hat{u}(f)$ is the frequency spectrum of $u(t)$ and $\left\langle f^2 \right\rangle$ is the average of f^2 weighted by $\left|\hat{u}(f)\right|^2$. Then, τ_c is:

$$\tau_c = \frac{2\pi}{\sqrt{r}} \qquad (3)$$



(a)

(b)

Figure 1. (a) Five major seismotectonic provinces in Iran delineated by Mirzaei et al. [17] and distribution of 20 events in Alborz region and (b) Epicentral distance and magnitude distribution of the employed data in Alborz region.

Small and large events yield short- and long-period initial motions, respectively. However, the slip motion is in general complex, and even a large event often begins with a small short-period motion, followed by a long period motion. Consequently, it is important to define the average period during the first motion, instead of the period of the first motion [8]. Therefore, τ_c is large for events enriched with low-frequency energy in the beginning.

One possible approach toward issuing reliable warning is to combine two or more relations in parallel for increasing reliability and avoiding of false alarms. Thus, the possible application of P_d in magnitude estimation from the few seconds of initial P-wave is also examined [5, 21, 22]. The P_d is determined from the initial 3 seconds of P-wave using vertical displacement records. The estimated P_d values show good correlation with the magnitudes, and are found to be much less sensitive to the cut-off frequency in displacement estimation from vertical accelerograms as will be explained in detail in the next section.

3. Data Prossesing and Analysis

A total of 654 horizontal and vertical accelerograms from 20 events was selected during the period from 1995 to 2013 for the analysis here. Table (1) shows the specifications of the selected events. Since the main goal of EEWS is to alarm the catastrophic earthquakes, the events with magnitude larger than 4.7 are employed. The vertical accelerograms are used to determine τ_c and P_d parameters. These accelerograms are digitized at 200 samples per second and were integrated two times to compute displacement waveforms. Although, the P-wave arrival time should be picked automatically in the operational phase, the onset of P-wave is manually picked in this stage for increasing the accuracy of the derived scaling relations. Thus, the selected 3-second time window of P-wave arrival will not be contaminated by S-wave for small epicentral distances. For estimating displacement waveform, it is necessary to remove undesired long-period trends and baseline drifts introduced by double integration. A common practice is to apply a causal 2-pole high-pass filter (usually Butterworth type)

Table 1. Specifications of the 20 events used in this study.

Origin Time (yyyy/mm/dd)	Latitude (^{0}N)	Longitude (^{0}E)	M_W	Number of the Stations
1995/10/15	37.06	49.53	5.1	1
1997/02/28 (Ardabil)*	38.30	48.06	6.1	6
1997/03/02	37.86	47.87	5.3	3
2002/04/19	36.67	49.74	5.2	13
2004/05/28 (Kojur-Firuzabad)*	36.55	51.58	6.3	21
2005/09/26	37.36	47.77	5.2	3
2008/09/02	38.69	45.79	5	9
2010/08/27 (Damghan (Kuh-Zar))*	35.58	54.48	5.7	3
2011/08/11	36.57	54.71	5	5
2012/01/11	36.38	52.74	5	13
2012/08/11 (Ahar –Varzaghan)*	38.52	46.86	6.5	21
2012/08/11 (Ahar –Varzaghan)*	38.36	46.80	6.4	28
2012/08/11	38.47	46.76	5.2	11
2012/08/15	38.35	46.61	5	13
2012/08/16	38.36	46.70	4.8	17
2012/11/07 (Varzaghan)*	38.45	46.52	5.6	15
2012/11/16	38.49	46.54	4.8	9
2012/12/23	38.49	44.84	5.1	9
2013/01/26	38.29	46.81	4.8	9
2013/04/18	38.39	45.37	4.9	9

*** Damaging Events**

with a 0.075 Hz cut-off frequency. The filter cut-off frequency need to be appropriately selected since it removes not only the artificial distortion, but also affect the low frequency content of the record, and therefore, the magnitude estimation by the parameters.

The BHRC data were recorded by SSA-2 accelerometers, which are very old recording system and cannot be updated due to the imposed sanctions to Iran. Therefore, it is important to check the applicability of this cut-off frequency to BHRC data, which their quality could be noticeably differed from the data recorded by the recent sophisticated recording systems employed in other countries. To this end, high-pass filter with different cut-off frequencies (0.075, 0.1, 0.12, 0.14, 0.16, 0.18, 0.2, and 0.22 Hz) are applied to vertical accelerograms. Then, the displacement waveforms of each record using different filters have been visually inspected one by one to select the best cut-off frequency. Figure (2) shows an example of calculated displacement waveforms along with the variation of estimated τ_c for different cut-off frequencies. The results show two different cut-off frequencies of 0.075 and 0.18 for the magnitudes of $M_W \geq 5.5$ and $M_W < 5.5$, respectively. This means that moderate earthquakes need larger cut-off frequencies than the strong (damaging) ones.

4. Magnitude Scaling Relations

Using different cut-off frequencies for two magnitude ranges, τ_c for each record and its average for the records of an event are calculated [3, 5, 7, 9, 10]. Then, the scaling relation between averaged τ_c and magnitude of the events is derived by using regression analysis as follows, Figure (3):

$$\begin{aligned} &\log(\tau_c) = 0.32 M_W - 1.33 \\ &SDV = 0.24 \\ &\text{or} \\ &M_{W(\tau_c)} = 3.1\log(\tau_c) + 4.2 \end{aligned} \tag{4}$$

Eq. (4) gives a standard deviation of 0.24 and correlation coefficient of 0.76, which supports its applicability in magnitude estimation for EEWS. The similar studies for Taiwan, Japan and USA (California) show the standard deviation and correlation coefficient in the range of 0.12-0.8 and 0.77-0.94, respectively [9, 10, 21, 22].

To examine the validity of the developed relation, it is also compared with those proposed by Wu and Kanamori [9, 10] as shown in Figure (3). From this

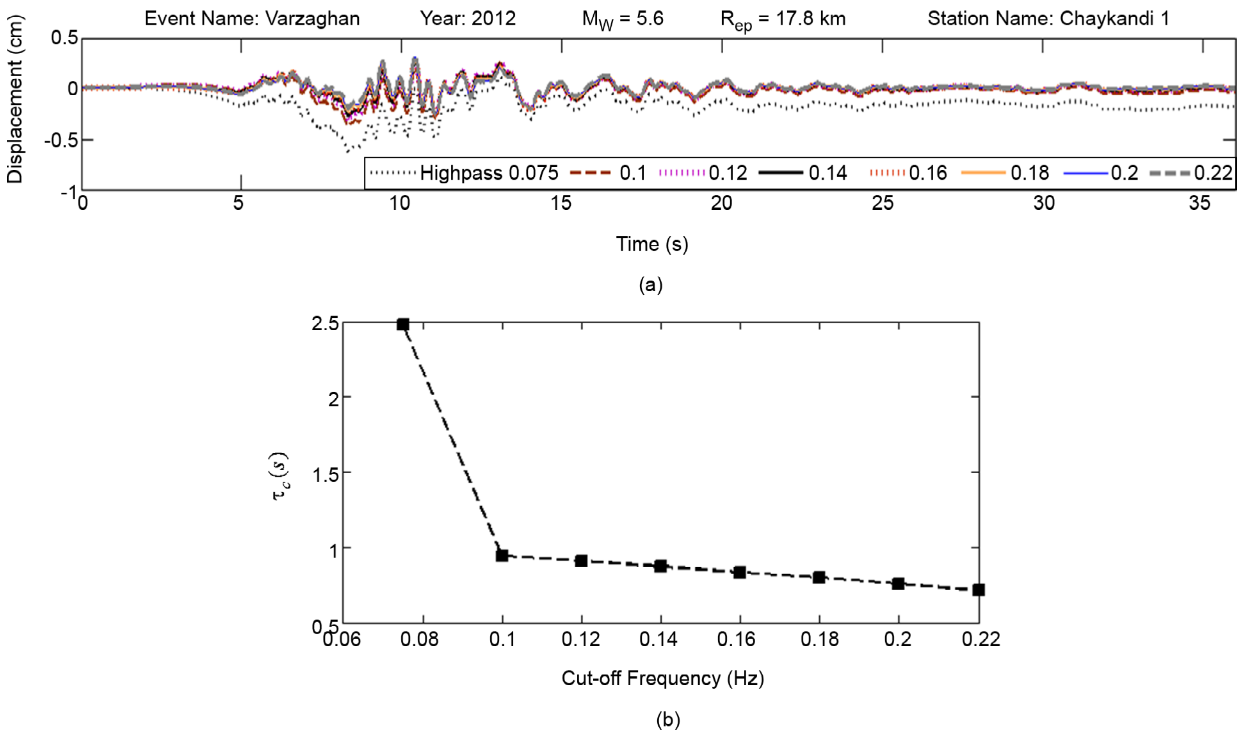


Figure 2. (a) An example of computed displacement waveform using various filter cut-off frequency, and (b) variation of τ_c versus different values of cut-off frequency.

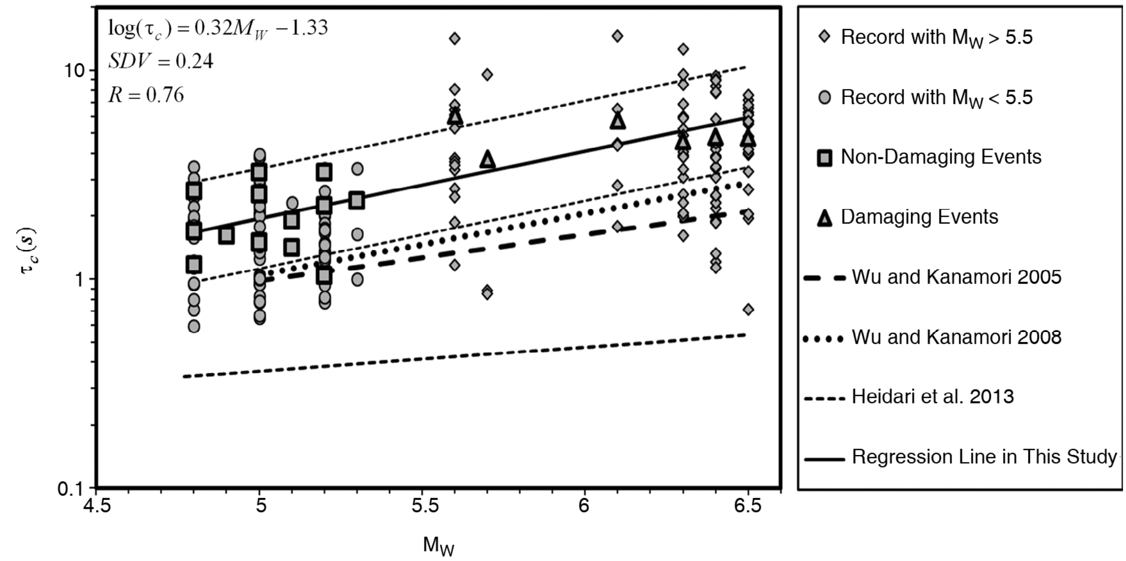


Figure 3. The estimated τ_c (grey circles) versus M_W. All averaged periods are determined based on high-pass filter with 0.075 Hz and 0.18 Hz cut-off frequencies for the events with $M_W \geq 5.5$ and $M_W < 5.5$, respectively. Solid line shows the least square fit, two thin dashed lines show plus and minus of one standard deviation.

figure, the slopes of two lines are almost the same, while the constant of the lines notably differ. Thus, it may not be eligible to use in Alborz region.

Heidari et al. [15] introduced scaling relation for Tehran (part of Alborz region) as:

$$M_L = 8.6\log(\tau_c) + 8.8 \quad (5)$$

This relation is derived based on 194 events around Tehran with the magnitude in the range of 2.5 to 4.6. They claim that this relation is applicable to use in EEWS for damaging earthquakes in spite of the magnitude limitation in their employed data. When compared the Eq. (5) with the proposed one here as well as the one given by Wu and Kanamori in Figure (3), the Heidari et al. relation shows large difference with both of the other two relations. It is noteworthy that the application of Heidari et al. relation could largely overestimated the earthquake magnitude in Alborz region, and thus in Tehran.

In spite of good correlation for Eq. (4), one big disadvantage remains that is the decision on the filter cut-off frequencies before an earthquake occurrence. To overcome this deficiency, the P_d parameter is examined and the relation between the estimated peak displacement of initial 3 seconds of P-wave and magnitude is inspected as shown in Figure (4). In estimating P_d parameter, all the records are simply filtered using conventional 0.075 cut-off frequency, and the scaling relation between P_d and M_w is developed in the same fashion as:

$$\log(P_d) = 0.51M_W - 3.48$$
$$SDV = 0.16$$
$$\text{or} \quad (6)$$
$$M_{w(P_d)} = 2\log(P_d) + 6.8$$

The correlation coefficient of above relation is 0.88, which is much larger than the one for τ_c parameter. This suggests that the P_d parameter is much less sensitive to the filter cut-off frequency than τ_c parameter. On the other hand, P_d parameter is the peak displacement amplitude of the initial P-wave, which can be attenuated with distance from the source. Meanwhile, the good correlation between the estimated P_d and magnitude confirm its independence to the distance within the epicentral range of the employed data (i.e. up to 90 km). This validates the application of the P_d parameter for EEWS in Alborz region in view of both distance and filter cut-off frequency. Furthermore, the P_d parameter can be used as an indicator of damaging earthquake as shown in Figure (4). From this figure, all damaging events have the P_d values bigger than 0.3 cm. Therefore, it can be used as a threshold value for separating damaging events from non-damaging ones.

In the next step, these two parameters (τ_c and P_d) are combined as $\tau_c \times P_d$ to check and possibly improve the reliability [5, 21, 22] by using both τ_c and P_d parameters. Figure (5) shows $\tau_c \times P_d$ values for all the events versus M_w. A linear correlation with magnitude is found as:

$$\log(\tau_c \times P_d) = 0.84M_W - 4.81$$
$$SDV = 0.53$$
$$\text{or} \qquad (7)$$
$$M_{W(\tau_c \times P_d)} = 1.21\log(\tau_c \times P_d) + 5.7$$

with a correlation coefficient of 0.87. It is noteworthy that this parameter also effectively discriminates the damaging events as indicated by triangle symbols in Figure (5) from non-damaging ones with the threshold value of 1.

5. A New EEW Algorithm for Alborz Region

Based on the results of the above analysis, a new algorithm is proposed for EEWS in Alborz region as depicted in Figure (6). First, an automatic P picker similar to that described by Allen [2] will be used to

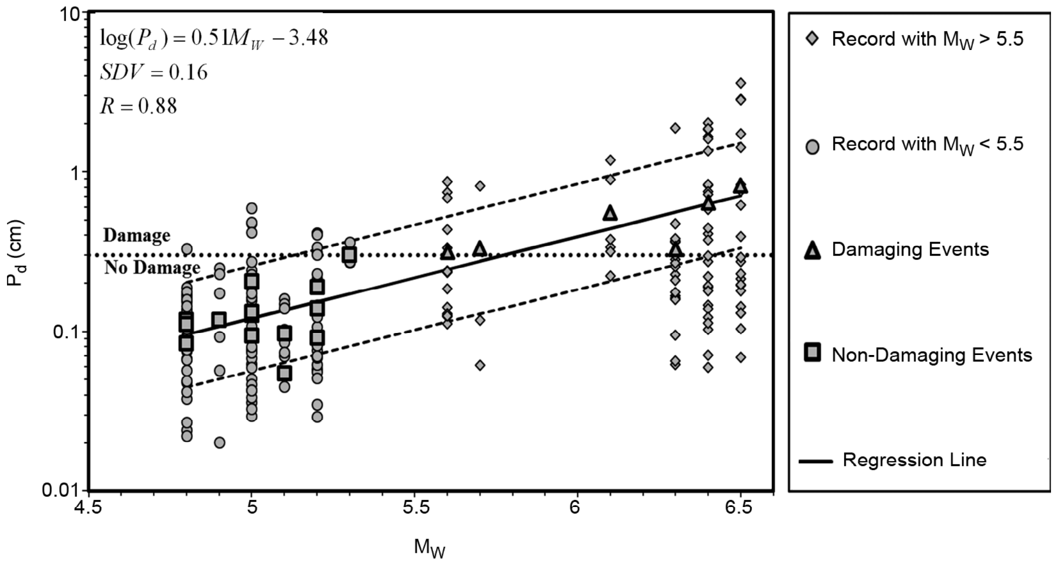


Figure 4. The estimated P_d (grey circles) versus M_w for Alborz region. Squares show the averaged P_d for the events. All Pd values are determined based on high-pass filter with 0.075 Hz cut-off frequency. Solid line shows the least square fit and two dashed lines show the range of one standard deviation. Horizontal line is the threshold to distinguish damaging and non-damaging events.

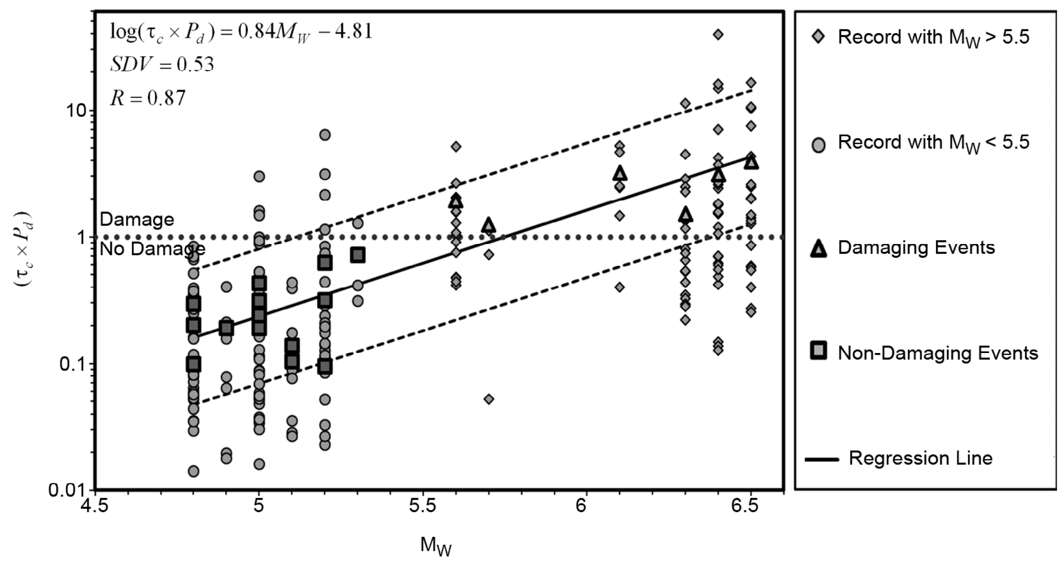


Figure 5. The relation between $\tau_c \times P_d$ and Mw for events of Alborz region. Solid line shows the least square fit for all 20 events and two dashed lines show the range of one standard deviation. Squares show the non-damaging events and triangles indicate the damaging events. Horizontal line is the threshold to distinguish the damaging events.

detect the P-wave arrival. Second, the P_d parameter is determined from vertical accelerograms using filter with 0.075 Hz cut-off frequency. Third, the P_d value is checked to discriminate between damaging and non-damaging event using the threshold value of 0.3 cm. If the value of P_d is less than 0.3 cm (i.e. non-damaging event and thus small magnitude), the τ_c will be estimated by using a high-pass filter with 0.18 Hz cut-off frequency; otherwise, the filter with 0.075 Hz cut-off frequency is used. Then, the $\tau_c \times P_d$ parameter is calculated.

According to the defined thresholds for P_d and $\tau_c \times P_d$, four cases can be assumed that are: 1) $P_d >$ 0.3 and $\tau_c \times P_d > 1$ that means a damaging event is

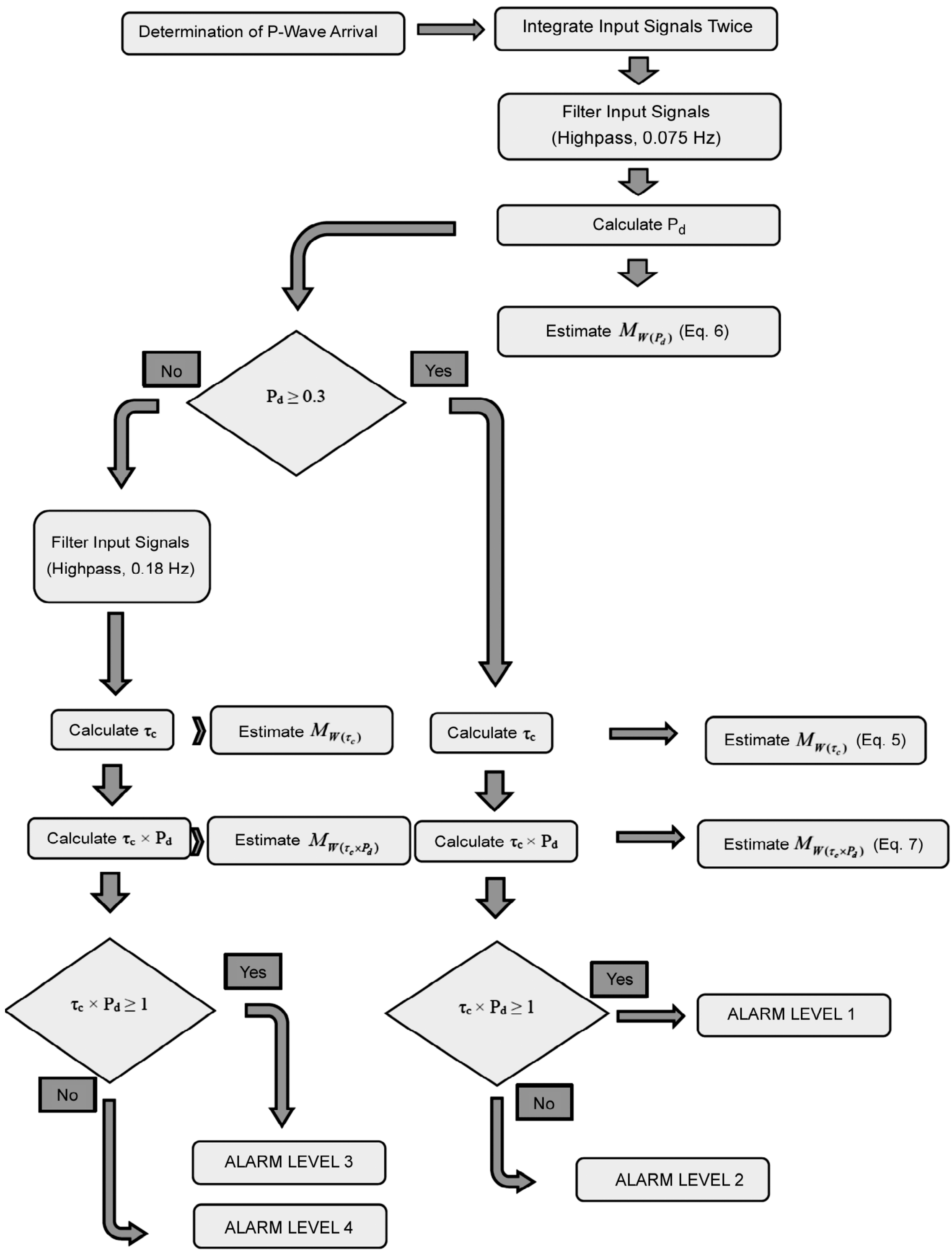


Figure 6. A flowchart of proposed algorithm for EEWS in Alborz based on defined threshold values of 0.3 and 1 for P_d and $\tau_c \times P_d$ parameters, respectively.

going to happen in both station and far areas; 2) P_d > 0.3 and $\tau_c \times P_d$ < 1 that means an event is damaging only in the limited area around the station; 3) P_d < 0.3 and $\tau_c \times P_d$ >1 that means an event is not damaging in the station area, but it can be damaging in far area; 4) P_d < 0.3 and $\tau_c \times P_d$ < 1 that means an event is not damaging in both station and far areas. In the first case, a global alarm should be issued, while in the second case only local alarm needs to be issued for the area around the station. In the third case, an alarm should be only issued to governmental users. Finally in the fourth case, no alarm is necessary to be issued.

The main target in EEWS is to increase earthquake early warning lead-time (the time between the alert notification and the arrival time of destructive S-wave at a given target site). Therefore, to increase lead-time, this procedure can be accomplished in each station and send only the required parameters (instead of displacement waveforms) to the control center, where decisions have been made. Furtheremore, to increase the reliability and accuracy in estimating the magnitude of oncoming event, the following relation is introduced to incoroporate all the parameters as:

$$M_W = 0.3M_{W(\tau_c)} + 0.35M_{W(P_d)} + 0.35M_{W(\tau_c \times P_d)} \quad (8)$$

Using Eq. (8), an event magnitude is estimated by the weigthed average of magnitudes by using the proposed relations of all three parameters, i.e. Eqs. (4), (6) and (7). Furthermore, the weights in this equation is assigned by normalizing the correlation coeffitients of the proposed relations in Eqs. (4), (6) and (7).

6. Conclusions

This study aims to present the scaling relations and a methodology using τ_c, P_d, and $\tau_c \times P_d$ parameters estimated from the initial three-second time window of P-wave arrival for EEW purposes in Alborz region, where Tehran is located in its southern part. To this end, three magnitude scaling relations using τ_c, P_d, and $\tau_c \times P_d$ parameters are introduced. These relations are derived using 654 accelerograms from 20 events recorded at BHRC stations in the magnitude range of 4.8 to 6.5. To examine the reliability of the proposed relations, they are compared with those developed by Wu and Kanamori [9-10] for a wide magnitude range and Heidari et al. [15] for a moderate magnitude range. A relatively good agreement with the results of Wu and Kanamori [9-10] was used to validate the developed relations. Furthermore, it reveals that the Heidari et al. relations overestimate the magnitude and need to be further examined.

A new early warning algorithm based on τ_c, P_d, and $\tau_c \times P_d$ parameters was developed. Four levels of warning were difined for alarming using P_d and $\tau_c \times P_d$ parameters with the determined threshold values of 0.3 and 1, respectively. Furthermore, to increase the reliability and accuracy in magnitude estimating, the earthquake magnitude is calculated by the new relation as a weighted average of estimated magnitudes from different parameters. This decreases the probability of false alarms and increases the performance of EEWS.

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