Analysis of Tauc (τc) and Pd attributes for Earthquake Early Warning in India

R. Bhardwaj, A. Kumar, M. L. Sharma
Department of Earthquake Engineering, Indian Institute of Technology Roorkee

SUMMARY:
One of the prerequisite for disaster mitigation and management is the apriori knowledge of impinging strong ground motion. Earthquake Early Warning systems are real-time systems (EEWS) that process and transmit information about the earthquake’s damage potential in a fast and reliable way, prior to the arrival of damaging seismic wave at user sites. EEWS relate initial parameters of the ground motion with the actual size of the impending earthquake. This study uses two parameters; ground motion period (τc) and a high-pass filtered vertical displacement amplitude (Pd) of initial 3 sec of the seismic waves for estimating magnitude (M) using Indian dataset. A comparison between the worldwide predicted τc - M and Pd - M relationships with calculated relationship have been made and the goodness of fit of the calculated Indian regressions have been determined. EEW can be a helpful approach for India to mitigate hazard and seismic risk as it has already proven itself in countries like Japan, Mexico, Taiwan, Romania and Turkey.

Keywords: Earthquake early warning (EEW), Primary waves (P waves), Magnitude

1. INTRODUCTION
India is situated on a peninsula extending into the Indian Ocean, with the Arabian Sea to the west and the Bay of Bengal to the east. Separated from the rest of Asia by the immense Himalayan ranges in the north, the Himalaya is one of the most seismic active mountains of the world and has been repeatedly hit by damaging earthquakes like Assam earthquake (1897, M=8.3), Kangra earthquake (1905, M=7.8), Nepal-Bihar earthquake (1934, M=8.6) and Assam earthquake (1950, M=8.7). In the last few decades the Kinnaur earthquake (1975, M=6.2), Dharchula earthquake (1980, M=6.1), Uttarkashi earthquake (1991, M=6.9), Chamoli earthquake (1999, M= 6.4) and the Kashmir earthquake (2005, M=7.6) have struck. The damages caused by the earthquakes will continue to increase as the population and construction grow. It is therefore essential for India to take measures to reduce earthquake losses through scientific research. For this viewpoint, EEW is becoming a practical tool to reduce the losses by giving warning before the arrival of a damaging ground motion (Kanamori et al, 1997; Wenzel et al., 2001). EEWS are also played an integral role in engineering applications. The main challenge for the effective use of EEW in engineering prospective is the longer response time taken by the structural control of buildings to activate on receiving EEW messages against strong shaking. Further efforts are needed to achieve engineering applications of the EEWS (Hsiao et al., 2011).

One of the prerequisite for disaster mitigation and management is the a priori knowledge of impinging strong ground motion. In this study we have made regressions between ground motion period (τc) vs magnitude and high-pass filtered vertical displacement amplitude (Pd) vs magnitude for Indian region. Calculated regressions are then compared with the worldwide predicted τc - M and Pd - M relations and a close resemblance has been observed. On linear averaging the magnitude estimated by two parameters (τc and Pd), a better estimate of magnitude has been obtained. The predicted equations are developed for ground motions of magnitude range 3.3 ≤ M ≤ 6.8 at an epicentral distance of 1 ≤ R ≤
60 km using 65 strong ground motion time histories. The derived prediction equation shows a consistency with other predictive relations currently in use for different region in the world.

2. EEWS AND GEOLOGY OF THE STUDY AREA

The main objective of an EEW system is fast and reliable estimation of earthquake’s damage potential which is necessary for earthquake disaster mitigation and management. EEWS provide warnings of an impending damage either by rapid estimate of earthquake source parameters or based on simple thresholds. The warning time is generally few seconds to few tens of seconds depending on the distances between seismic source, seismic sensor and user sites. The important objectives of EEWS are: Event detection and location, magnitude estimation, peak ground motion prediction at the target site and alert notification (Satriano et al., 2011). There are two types of EEWS used around the world. First is front detection/regional warning system in which seismometers installed in the earthquake source area give early warnings to more distant area user. Second is an onsite warning system, which determines the earthquake parameters from the initial portion of the P waves and predict the possible ground motion of the following S-wave at the same site. An onsite warning approach is considered to be fast as compared to regional warning approach but reliability of warning is better achieved in case of regional warning approach.

The northern part of the India is in the vicinity of Himalayas. The Himalayas are the result of continent-continent collision and accounts for approximately 15% of yearly global seismic energy release. The collision of Indo and Eurasian plates produced the Himalayas and the Tibetan Plateau which has the most noticeable topography in the world (Acharya and Narula, 1998). The Himalayas active seismicity has resulted in tremendous loss of life and property due to tremendous increase of urbanization and industrialization in the regions closed to the Himalayas. The whole Himalayan belt (around 2,500 km) comprises of many states like Jammu and Kashmir, Himachal Pradesh, Punjab, Harayana, Uttarakhand, Sikkim, Assam, Meghalaya, Arunachal Pradesh, Manipur, Mizoram etc which are thickly populated. In the present paper, we formulate relations between P - waves initial parameters with the final size of the earthquake for India region using a time window of 3 sec to issue warning as already used in many countries like Japan (Nakamura, 1988; Odaka et al., 2003; Kamigachi, 2004), Mexico (Espinosa-Aranda et al., 1995, 2009; Suarez et al., 2009), Taiwan (Wu et al., 1999, 2002, 2007), Romania (Wenzel et al., 1999; Böse et al., 2007), California (Allen and Kanamori, 2003; Allen et al., 2009; Wurman et al., 2007; Cua et al., 2007), Turkey (Erden et al., 2003; Böse et al., 2008; Alcik et al., 2009) and Italy (Iannaccone et al., 2009; Satriano et al., 2010).

3. DATABASE

The data used in this study has been compiled from Indian dataset (www.pesmos.in), a strong-motion instrumentation network of Indian Institute of Technology, Roorkee (IITR) which collects data from 293 strong-motion accelerographs installed in Indian Himalayan range from Jammu and Kashmir to Meghalaya. The digital strong motion accelerograph consists of internal AC-63 GeoSIG triaxial force-balanced accelerometers and GSR-18 GeoSIG 18-bit digitizer with external GPS. The average station-to-station distance of the network is about 40 to 50 km (Kumar et al., 2012). In the present study vertical component of 65 individual station records of 31 events have been used. The magnitudes of these seismic events were in the range from 3.3 to 6.8 at an epicentral distance of less than 60 km. The dataset also include three events namely Dharmsala earthquake $M_w$ 5.4 (1986), Uttarkashi earthquake $M_w$ 6.8 (1991) and Chamoli earthquake $M_w$ 6.5 (1999) which have been recorded by earlier strong-motion network of IITR which used SMA-1 analog accelerographs with trigger threshold of 0.01 cm/sec$^2$. The analog accelerographs were manually digitized, interpolated at 50 SPS and filtered (0.17-0.20; 25-27 Hz) using Ormsby filter (Chandrasekaran and Das, 1992). Figure 3.1. displays the distribution of earthquakes with respect to epicentral distance.
4. METHODOLOGY

The present study is based on two characteristic parameters obtained from first few second of P-wave (τc and Pd). τc is a measure of the average period of ground motion within some specific time window. It was first introduced by Kanamori (2005) and is a modified form of the method developed by Nakamura (1988). The period parameter τc, from the initial 3 sec of P waves. τc is determined as

\[ \tau_c = \frac{2\pi}{\sqrt{r}} \]  (4.1)

where, \( r = \frac{\int_0^{\tau_o} \ddot{u}(t)dt}{\int_0^{\tau_o} u(t)dt} \), \( \tau_o = \) duration of record used (usually 3 sec), \( \ddot{u}(t) = \) velocity and \( u(t) = \) displacement obtained from ground motion record on double integration. The larger the τc the larger the event. Further a series of studies have been performed regarding τc approach (Wu and Kanamori, 2005a; Wu and Kanamori, 2005b; Wu et al., 2006; Wu et al., 2007; Wu and Kanamori, 2008a; Wu and Kanamori, 2008b, Sokolov et al., 2009, Shieh et al., 2011, Alcik et al., 2011). \( Pd \), which is peak displacement amplitude of P-wave calculated within a time specified time window, was used in ElarmS methodology (Wurman et al., 2007) for magnitude estimation. Different τc-M and Pd-M relationships have been given by different researchers (Table 4.1 and Table 4.2) for different regions of the world by a simple linear regression model among the logarithmic τc, logarithmic Pd and the reported magnitude.

\[ \log(\tau_c) = A \times M + B \pm \sigma_{log \tau_c} \]  (4.2)

\[ \log(Pd) = C \times M + D \pm \sigma_{log \ Pd} \]  (4.3)

where A, B, C and D are constants to be determined from the regression analysis. \( \sigma_{log \tau_c} \) and \( \sigma_{log \ Pd} \) is the standard error associated with the distribution of random variables \( \log(\tau_c) \) and \( \log(Pd) \).

<table>
<thead>
<tr>
<th>Serial Number</th>
<th>Regression relationships between τc and magnitude</th>
<th>References</th>
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<tbody>
<tr>
<td>1</td>
<td>( \log(\tau_c) = 0.237M - 1.462 \pm 0.091 )</td>
<td>Wu et al., 2007</td>
</tr>
<tr>
<td>2</td>
<td>( \log(\tau_c) = 0.267Mw - 1.462 \pm 0.159 )</td>
<td>Sokolov et al., 2009</td>
</tr>
<tr>
<td>3</td>
<td>( \log(\tau_c) = 0.221Mw - 1.113 \pm 0.0845 )</td>
<td>Wu et al., 2005</td>
</tr>
<tr>
<td>4</td>
<td>( \log(\tau_c) = 0.296M - 1.716 \pm 0.122 )</td>
<td>Wu et al., 2008a</td>
</tr>
<tr>
<td>5</td>
<td>( \log(\tau_c) = 0.21M - 1.19 \pm 0.25 )</td>
<td>Zollo et al., 2010</td>
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In the present study, we considered 65 vertical component of Indian strong motion records as already discussed in above section. These records were integrated to obtain velocity and displacement. A high-pass fifth order Butterworth filter with a cutoff frequency of 0.075 Hz was applied on the record to remove the low frequency drift in velocity and displacement signal. Following previous studies, we adopted a time window length of 3 sec starting from the P-wave arrival time in magnitude estimation. The value of $\tau_c$ and $P_d$ have been calculated for each individual station record and regression coefficients are obtained on average value of $\tau_c$ and $P_d$ with magnitude for each earthquake. The calculated regression is compared with regressions given for other regions of the world, to check goodness of fit. Finally for more accurate and reliable magnitude estimation a simple linear average of the magnitude estimated by $\tau_c$ and $P_d$ has been done and the calculated magnitude is compared with catalog magnitude.

**5. RESULTS**

Regressions were performed between $\tau_c$ and magnitude as well as $P_d$ and magnitude for the dataset. The coefficients A, B, C and D of Eqn. 4.2. and Eqn. 4.3. are determined as follows:

\[
\log(\tau_c) = 0.2205M - 1.3048 \pm 0.1830 \\
\log(P_d) = 0.498M - 4.5161 \pm 0.518
\]

We can invert the regression results in Eqn. 5.3 and Eqn. 5.4 to estimate the magnitude $M$ from $\tau_c$ and $P_d$.

\[
M = 2.4605 \log(\tau_c) + 5.2399 \pm 0.6114 \\
M = 0.8638 \log(P_d) + 6.4284 \pm 0.6823
\]

Fig. 5.1.a and 5.1.b. shows variation of $\tau_c$ and $P_d$ values versus magnitude. The solid lines represent the linear best fit to the data and the dash lines represent the standard deviation in the $\tau_c$ and $P_d$ values. The distribution of $\tau_c$ values with respect to magnitude show that scattering is higher in low magnitudes bins ($3 \leq M \leq 4.5$). Fig. 5.1.a. reveals that for higher magnitude earthquakes $\tau_c$ is observed to be greater than 1 sec. However from Fig. 5.1.b. it is clear that $P_d$ value shows high scattering for higher magnitude generally $M \geq 5$ and above.

Fig. 5.2.a. and 5.2.b. represent the comparative plotting of the predicted regressions calculated from Indian dataset with the regressions given by many researchers (see Table 4.1. and Table 4.2.) for different regions of the world using different datasets. Fig. 5.2.a. shows that the derived prediction equation is within a reasonable consistency with the other predictive relations currently in use for different parts of the world. Figure 5.2.b. shows that the scaling relation for India has a smaller slope to that of northern California (Wurman et al., 2007) and Japan (Brown et al., 2009). The displacements at all magnitude is also lower in comparison to northern California and Japan which implies that India has higher attenuation than northern California and Japan. Due to less Indian strong motion data available for higher magnitudes, the regression results obtained for $P_d$ may not be reliable but these are conservative.
Figure 5.1. Plots of regression curve (solid lines). The two dashed lines represent the standard deviation. Plus represents \( \tau_c \) and Pd values at each station and red solid triangle represents average value of \( \tau_c \) and Pd for the event. (a) \( \tau_c \) vs magnitude plot (b) Pd vs magnitude plot for Indian data.

Figure 5.2. Comparison of Predicted regression calculated from Indian data with the regressions given by different researchers of the world. Dash and dot lines represent the other researcher’s attenuation equation and red solid line represents the predicted attenuation equation. (a) \( \tau_c \) vs magnitude plot (b) Pd vs magnitude plot for comparing goodness of fit of predicted regression.

The two magnitudes estimated from \( \tau_c \) and Pd parameters for a time window of 3 sec after P-onset are linear averaged together to create the predicted magnitude estimate for each event, which is used for predicting ground shaking. Fig. 5.3. shows that the average magnitude (red triangles) lies more close to the linear best fit (solid line) between predicted (Mp) and catalog (Mc) magnitude, which confirms that the scattering and saturation effect of \( \tau_c \) and Pd at higher and lower magnitudes gets improved using average of the two estimated magnitudes by the parameters. The regression between Mc and Mp is given as:

\[
Mc = 1.0676 \, Mp - 0.396 \pm 0.6354
\]
Figure 5.3. Plot of Predicted magnitude vs Catalog magnitude. Plus represents magnitude using only $\tau_c$, the cross are magnitude estimate using $P_d$ and the solid red triangle is the average of the $P_d$ and $\tau_c$ magnitudes for that event.

6. CONCLUSIONS

An endeavor has been made to estimate the parameters for earthquake early warning system useful in disaster mitigation and management, Indian dataset has been used to generate prediction equation for estimation of magnitude from initial part of $P$ wave. Regression relationships for $\tau_c$ and $P_d$ with magnitude have been calculated. The dataset is covering a magnitude range between 3.3 to 6.8 and an epicentral distance up to 60 km. Since, no such regression relationship has been found for Indian region, we compared derived relationship with similar relationships derived by other authors for other parts of world. The predicted equations using Indian dataset show similar trend. It may be mentioned that linear regression between catalog and predicted magnitude gives standard deviation of 0.6 which is quite high. Therefore it is required that, to avoid missed and false alarm, magnitude estimation should be done by averaging more early warning attributes like $\tau_p^{\text{max}}$ (maximum predominant period) and CAV (cumulative absolute velocity) etc. along with $\tau_c$ and $P_d$ to get better estimation of the size of earthquake. EEW can be a helpful approach for India to mitigate hazard and seismic risk as it has already proven itself in countries like Japan, Mexico, Taiwan, Romania and Turkey. A better estimation of parameters will lead to better disaster mitigation and management in highly seismic areas like Himalayas.

REFERENCES


