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

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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 (τ_c) 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 τ_c - 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 (τ_c) vs magnitude and high-pass filtered vertical displacement amplitude (Pd) vs magnitude for Indian region. Calculated regressions are then compared with the worldwide predicted τ_c - M and Pd - M relations and a close resemblance has been observed. On linear averaging the magnitude estimated by two parameters (τ_c and Pd), a better estimate of magnitude has been obtained. The predicted equations are developed for ground motions of magnitude range $3.3 \leq M \leq 6.8$ at an epicentral distance of $1 \leq R \leq$

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 (Erdik 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.

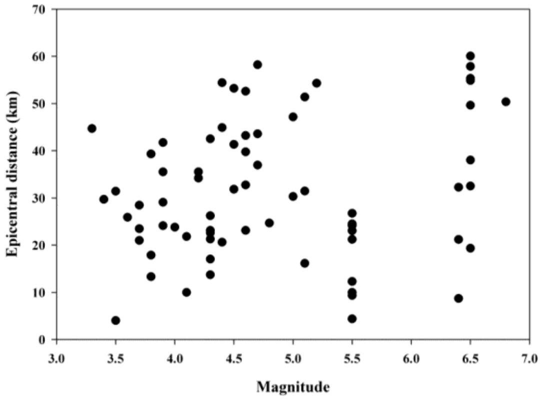


Figure 3.1. Distribution of the seismic events with respect to epicentral distance and magnitude used in the study

4. METHODOLOGY

The present study is based on two characteristic parameters obtained from first few second of P-wave (τ_c and Pd). τ_c 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 τ_c, from the initial 3 sec of P waves. τ_c is determined as

$$\tau_c = \frac{2\pi}{\sqrt{r}} \tag{4.1}$$

where, $r = \frac{\int_0^{\tau_0} \dot{u}^2(t)dt}{\int_0^{\tau_0} u(t)dt}$, τ_o = duration of record used (usually 3 sec), $\dot{u}(t)$ = velocity and $u(t)$ = displacement obtained from ground motion record on double integration .The larger the τ_c the larger the event. Further a series of studies have been performed regarding τ_c 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 τ_c-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 τ_c, logarithmic Pd and the reported magnitude.

$$\log(\tau_c) = A*M + B \pm \sigma_{log\tau c} \tag{4.2}$$

$$\log(Pd) = C*M + D \pm \sigma_{logPd} \tag{4.3}$$

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

Table 4.1. τ_c – M relationships given by different researchers

Serial Number	Regression relationships between τ_c and magnitude	References
1	$\log(\tau_c) = 0.237M - 1.462 \pm 0.091$	Wu et al., 2007
2	$\log(\tau_c) = 0.267Mw - 1.462 \pm 0.159$	Sokolov et al., 2009
3	$\log(\tau_c) = 0.221Mw - 1.113 \pm 0.0845$	Wu et al., 2005
4	$\log(\tau_c) = 0.296M - 1.716 \pm 0.122$	Wu et al., 2008a
5	$\log(\tau_c) = 0.21M - 1.19 \pm 0.25$	Zollo at al., 2010

Table 4.2. Pd – M relationships given by different researchers

Serial Number	Regression relationships between Pd and magnitude	References
1	$\log(Pd) = 0.73M_w - 3.77$	Wurman et al., 2007
2	$\log(Pd) = 0.66M_L - 4.02$	Brown et al., 2009

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 τ_c and Pd have been calculated for each individual station record and regression coefficients are obtained on average value of τ_c and Pd 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 magnitudes estimated by τ_c and Pd has been done and the calculated magnitude is compared with catalog magnitude.

5. RESULTS

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

$$\log(\tau_c) = 0.2205\, M - 1.3048 \pm 0.1830 \tag{5.1}$$

$$\log(\mathrm{Pd}) = 0.498\, M - 4.5161 \pm 0.518 \tag{5.2}$$

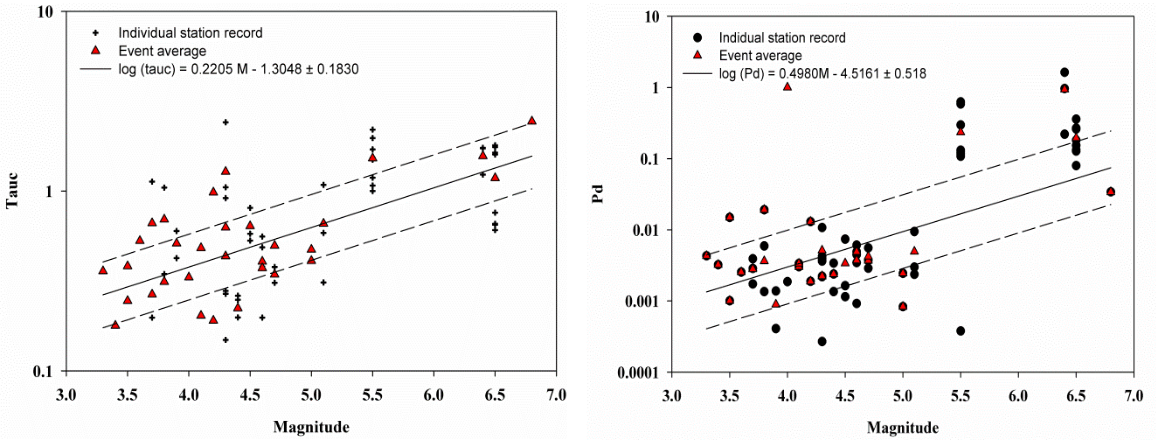
We can invert the regression results in Eqn. 5.3 and Eqn. 5.4 to estimate the magnitude M from τ_c and Pd.

$$M = 2.4605 \log(\tau_c) + 5.2399 \pm 0.6114 \tag{5.3}$$

$$M = 0.8638 \log(Pd) + 6.4284 \pm 0.6823 \tag{5.4}$$

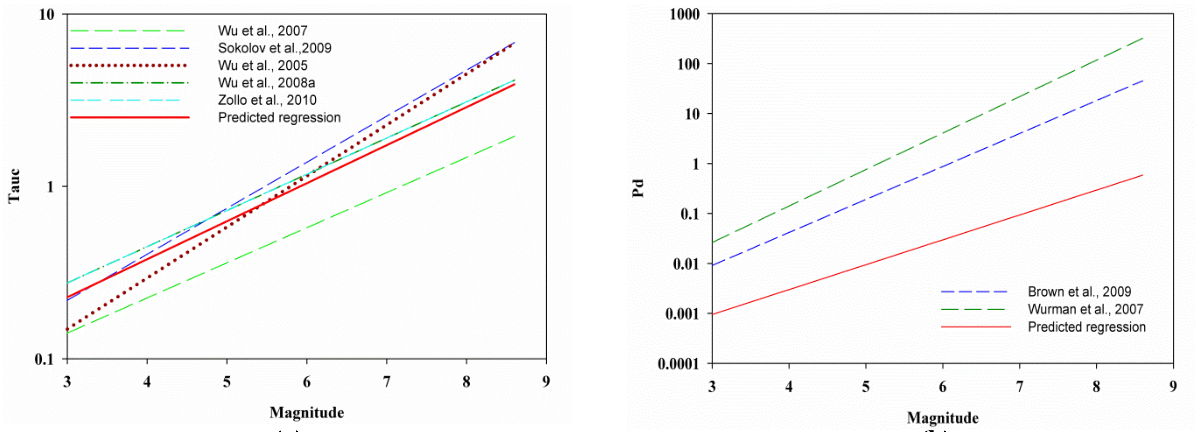
Fig. 5.1.a. and 5.1.b. shows variation of τ_c and Pd values versus magnitude. The solid lines represent the linear best fit to the data and the dash lines represent the standard deviation in the τ_c and Pd values. The distribution of τ_c values with respect to magnitude show that scattering is higher in low magnitudes bins ($3 \leq M \leq 4.5$). Fig. 5.1.a. reveals that for higher magnitude earthquakes τ_c is observed to be greater than 1 sec. However from Fig. 5.1.b. it is clear that Pd 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 Pd may not be reliable but these are conservative.



(a) (b)

Figure 5.1. Plots of regression curve (solid lines). The two dashed lines represent the standard deviation. Plus represents τ_c and Pd values at each station and red solid triangle represents average value of τ_c and Pd for the event. (a) τ_c vs magnitude plot (b) Pd vs magnitude plot for Indian data.



(a) (b)

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) τ_c vs magnitude plot (b) Pd vs magnitude plot for comparing goodness of fit of predicted regression.

The two magnitudes estimated from τ_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 τ_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:

$$Mc = 1.0676\, Mp - 0.396 \pm 0.6354 \tag{5.5}$$

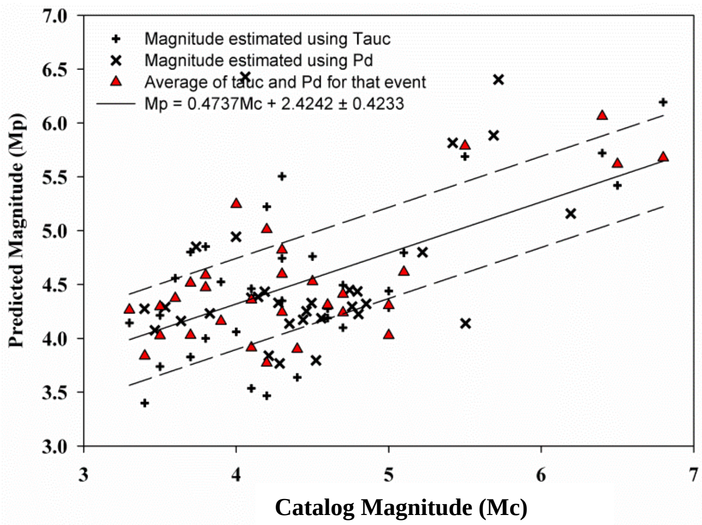


Figure 5.3. Plot of Predicted magnitude vs Catalog magnitude. Plus represents magnitude using only τ_c, the cross are magnitude estimate using Pd and the solid red triangle is the average of the Pd and τ_c magnitudes for that event.

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 τ_c and Pd 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 τ_p^{max} (maximum predominant period) and CAV (cumulative absolute velocity) etc. along with τ_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

Acharya, S. K. and Narula, P. L. (1998). Seismotectonic scenario of Himalaya and its recent developments. Eleventh Symposium on Earthquake Engineering, **Vol I**, 3-19.

Alcik, H., Ozel, O., Apaydin, N. and Erdik, M. (2009). A study on warning algorithm for Istanbul early warning system. Geophysical Research Letters **36**, 1-3.

Alcik, H., Ozel, O., Wu, Y.M., Ozel, N, M. and Erdick, M. (2011). An alternative approach for the Istanbul earthquake early warning system. Soil dynamics and Earthquake Engineering 31:2, 181-187.

Allen, R. M., Brown, H., Hellweg, M., Khainovski, O., Lombard, P. and Neuhauser, D. (2009). Real- time earthquake detection and hazard assessment by ElarmS across California. Geophysical Research Letters 36: 5, 1-6.

Allen, R.M. and Kanamori, H. (2003). The potential for earthquake early warning in Southern California. Science 300:5620, 786–789.

Böse, M., Ionescu, C. and Wenzel, F. (2007). Earthquake early warning for Bucharest, Romania: novel and revisited scaling relations. Geophysical Research Letters 34, 1-4.

Böse, M., Wenzel, F. and Erdik, M. (2008). PreSEIS: a neural network based approach to earthquake early warning for finite faults. Bulletin of the Seismological Society of America 98:1, 366–382.

Brown, H. M., Allen, R. M. and Grasso, V. F. (2009). Testing ElarmS in Japan. Seismological Research Letter 80:5, 727-739.

Chandrasekaran, A. R., and Das, J.D. (1992). Memoire of Geological Survey of India **23**, 81-122.

Cua, G. and Heaton, T. (2007). The Virtual Seismologist (VS) method: a Bayesian approach to earthquake early warning. In: Gasparini, P., Manfredi, G., Zschau, J. (Eds.) Earthquake Early Warning Systems. Springer, Berlin, pp. 97–132.

Erdik, M., Fahjan, Y., Ozel, O., Alcik, H., Mert, A. and Gul, M. (2003). Istanbul earthquake rapid response and the early warning system. Bulletin of Earthquake Engineering 1:1, 157– 163.

Espinosa-Aranda, J.M., Cuellar, A., Garcia, A., Ibarrola, G., Islas, R., Maldonado, S. and Rodriguez, F.H. (2009). Evolution of the Mexican seismic alert system (SASMEX). Seismological Research Letters 80:5, 694–706.

Espinosa-Aranda, J.M., Jiménez, A., Ibarrola,G., Alcantar, F., Aguilar, A., Inostroza, M. and Maldonado,S. (1995). Mexico city seismic alert system. Seismological Research Letters 66:6, 42–53.

Hsiao, N.C., Wu, Y. M., Zhao, L., Chen, D.Y., Huang, W. T., Kuo, K. H., Shin, T.C., Leu, P. L. (2011). A new prototype system for earthquake early warning in Taiwan. Soil Dynamics and Earthquake Engineering, 31:2 , 201-208.

Iannaccone, G., Zollo, A., Elia, L., Convertito, V., Satriano, C., Martino, C., Festa, G., Lancieri,M., Bobbio, A., Stabile, T.A., Vassallo, M. and Emolo, A. (2009). A prototype system for earthquake early-warning and alert management in southern Italy. Bulletin of Earthquake Engineering 8, 1105-1129.

Kamigaichi, O., (2004). JMA earthquake early warning. Journal of Japan Association of Earthquake Engineering 4:3, 134–137.

Kanamori, H., (2005). Real-time seismology and earthquake damage mitigation. Annual Review of Earth and Planetary Sciences 33, 195-214.

Kanamori, H., Hauksson, E. and Heaton, T. (1997). Real-time seismology and earthquake hazard mitigation. Nature 390, 461–4.

Kumar, A., Mittal, H., Sachdeva, R. and Kumar, A., (2011). Indian strong motion instrumentation network. Seismological Research Letters, 83:1, 29-36.

Nakamura, Y. (1988). On the urgent earthquake detection and alarm system (UrEDAS). Ninth World Conference on Earthquake Engineering, Japan, Vol. VII, 673– 678.

Odaka, T., Ashiya, K., Tsukada, S., Sato, S., Ohtake, K. and Nozaka, D. (2003). A new method of quickly estimating epicentral distance and magnitude from a single seismic record. Bulletin of the Seismological Society of America 93:1, 526–532.

Satriano, C., Wu,Y. M., Zollo, A. and Kanamori, H. (2011). Earthquake early warnings: Concepts, methods and physical grounds. Soil Dynamics and Earthquake Engineering 31, 106-118.

Satriano, C., Elia, L., Martino, C., Lancieri, M., Zollo, A. and Iannaccone, G. (2010). PRESTo, the earthquake early warning system for Southern Italy: concepts, capabilities and future perspectives. Soil Dynamics and Earthquake Engineering 31:2, 137-153.

Shieh, J. T., Wu, Y. M., Zhao, L., Chao, W. A. and Wu, C.F. (2011). An examination of τ_c-Pd earthquake early warning method using a strong motion building array. Soil Dynamics and Earthquake Engineering 31:2, 240-246.

Sokolov, V.,Wenzel, F. and Furumura, T. (2009). On estimation of earthquake magnitude in earthquake early warning systems. Earth Planets and Space 61, 1275–1285.

Wenzel, F., Baur, M., Fiedrich, F., Ionescu, C. and Oncescu, M. (2001). Potential of earthquake early warning system. Natural Hazard 23, 407–16.

Wenzel, F., Oncescu, M.C., Baur, and M. Fiedrich, F. (1999). An early warning system for Bucharest. Seismological Research Letters **70:2**, 161–169.

Wu, Y. M and Kanamori, H. (2005a). Experiment on an onsite early warning method for the Taiwan early warning system. Bulletin of the Seismological Society of America 95, 347-353.

Wu, Y. M. and Kanamori, H. (2005b).Rapid assessment of damaging potential of earthquakes in Taiwan from the beginning of P Waves. Bulletin of the Seismological Society of America 95, 1181-1185.

Wu, Y. M., Kanamori, H., Allen, R. and Hauksson, E. (2007). Determination of earthquake early warning parameters, τ_c and Pd , for southern California. Geophysical Journal International 170, 711-717.

Wu, Y. M. and Zhao, L. (2006). Magnitude estimation using the first three seconds P-wave amplitude in earthquake early warning. Geophysical Research Letters 33, pp. 4.

Wu, Y. M. and H. Kanamori (2008a). Development of an earthquake early warning system using real-time strong motion signals. Sensors 8, 1-9.

Wu, Y. M. and H. Kanamori (2008b). Exploring the feasibility of onsite earthquake early warning using close-in records of the 2007 Noto Hanto earthquake. Earth, Planets, and Space 60, 155-160.

Wu, Y. M., Chung, J.K., Shin, T.C., Hsiao, N.C., Tsai, Y.B., Lee, W.H.K., Teng,T.L., 1999. Development of an integrated seismic early warning system in Taiwan—case for Hualien area earthquakes.Terresrial, Atmospheric and Oceanic Sciences 10:4, 719–736.

Wu, Y. M., Hsiao, N.C., Lee, W.H.K., Teng, T. L. and Shin, T.C. (2007). State of the art and progress in the earthquake early warning system in Taiwan. In: Gasparini, P., Manfredi, G., Zschau, J. (Eds.) Earthquake Early Warning Systems, Springer, Berlin, pp. 283–306.

Wu, Y. M. and Teng. T. L. (2002). A virtual sub-network approach to earthquake early warning. Bulletin of the Seismological Society of America 92:5, 2008–2018.

Wurman, G., Allen, R.M. and Lombard, P. (2007). Toward earthquake early warning in Northern California. Journal of Geophysical Research 112, 1-19.

Zollo, A., Amoroso, O., Lancieri, M., Wu, Y. M. and Kanamori, H. (2010). A threshold-based earthquake early warning using dense accelerometer networks. Geophysical Journal International 183, 963-974.