A study on warning algorithms for Istanbul earthquake early warning system

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[1] 17 August (*M*w 7.4) and 12 November 1999 (*M*w 7.2) earthquakes have caused major concern about future earthquake occurrences in Istanbul and in the Marmara Region. Stress transfer studies and renewal model type probabilistic investigations indicate about 2% annual probability for a M_w = 7+ earthquake in the Marmara Sea. As part of the preparations for the expected earthquake in Istanbul, an early warning system has been established in 2002. A simple and robust algorithm, based on the exceedance of specified threshold time domain amplitude and the cumulative absolute velocity (CAV) levels, is implemented for this system. Rational threshold levels related to new bracketed CAV window approach (BCAV-W) are determined, based on dataset of strong ground motion records with fault distances of less than 100 km, as 0.2 m/s, 0.4 m/s and 0.7 m/s related to three alarm levels which will be incorporated in the Istanbul earthquake early warning system. **Citation:** Alcik, H., O. Ozel, N. Apaydin, and M. Erdik (2009), A study on warning algorithms for Istanbul earthquake early warning system, *Geophys. Res. Lett.*, *36*, L00B05, doi:10.1029/2008GL036659.

1. Introduction

[2] As increasing urbanization is taking place worldwide, earthquake hazards pose serious threats to lives and properties in urban areas. Recent advances in seismic instrumentation and telecommunication technologies permit the implementation of earthquake early warning systems that hold the potential to reduce the damaging affects of large earthquakes by giving a few seconds to a few tens of seconds warning before the arrival of damaging ground motion. Early warning systems, based on real-time automated analysis of ground motion measurements, play a role in reducing the impact of catastrophic events on industrial and densely populated areas, particularly, for mitigating earthquake related cites, explosions and hazardous material releases associated with strategic facilities and lifelines. In the past two decades, progress has been made towards implementation of earthquake early warning in Japan [*Nakamura*, 1988], Mexico [*Espinosa-Aranda et al.*, 1995], Taiwan [*Wu et al.*, 1999], Romania [*Wenzel et al.*, 1999], Southern California-USA [*Allen and Kanamori*, 2003], Turkey [*Erdik et al.*, 2003; *Böse et al.*, 2008] and Italy [*Olivieri et al.*, 2008].

[3] Frequent occurrence of historic destructive earthquakes clearly demonstrates the high seismic activity and the potential seismic hazard in the Marmara Region. Two recent destructive earthquakes, the Izmit (Kocaeli) earthquake of 17 August 1999 (*M*w 7.4) and the Duzce earthquake of 12 November 1999 (*M*w 7.2), that occurred along the western part of the North Anatolian Fault Zone have caused major concern about future earthquake occurrences and their possible consequences in the Istanbul area. Current probabilistic estimates of a major earthquake in İstanbul is about 2% per annum [*Erdik et al.*, 2004]. As part of the preparations for the future earthquake in Istanbul, an earthquake rapid response and an early warning system in the metropolitan area (IERREWS, or shortly I-NET) has been implemented in 2002 [*Erdik et al.*, 2003]. Currenty scheduled applications of I-NET include the traffic control applications at the FSM Suspension Bridge and Marmaray Tube Tunnel across the Bosporus Straits. The on-line structural health monitoring data from both of these crossings will be integrated with the early warning data to issue an automatic alarm signal to respective operation centers for traffic control. A comprehensive study on the development of such an integrated algorithm is being pursued with the Turkish State Highways authorites. Another application will be in connection with the IGDAS (Istanbul Natural Gas Distribution Network). This application includes the actuation of the automatic shut-off valves at the regulator stations upon the receipt of early warning signal and the exceedance of certain threshold ground motion quantity at the station itself.

[4] For the Istanbul earthquake early warning system (here after IEEWs) ten strong motion stations were installed along the northern shoreline of the Marmara Sea as close as to the main Marmara fault in on-line mode (Figure 1).

[5] In this study, in order to determine the threshold levels used in the IEEWs, we investigated the relationships of the windowed Bracketed Cumulative Absolute Velocity (BCAV-W) versus epicentral distance and magnitude.

2. Present Algorithm of the IEEW System

[6] Considering the complexity of fault rupture and the short fault distances involved, a simple and robust early warning algorithm, based on the exceedance of specified threshold time domain amplitude levels is implemented. The band-pass filtered peak ground acceleration (PGA) and the CAV are compared with specified threshold levels. When any PGA or CAV (the time integral of the absolute acceleration over the duration of the earthquake record) on any channel, in a given station, exceeds specific threshold values (currently set at 0.05, 0.1 and 0.2 m/s^2) it is considered a vote. Whenever we have votes from at least 3 stations for

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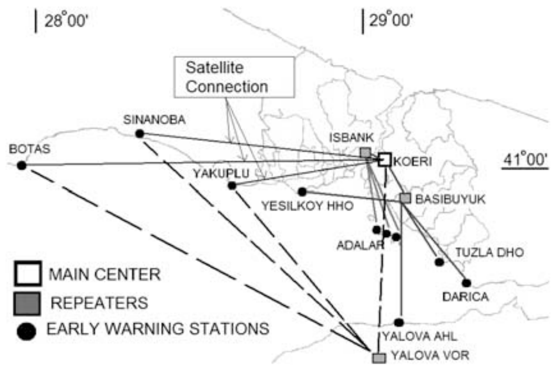

Figure 1. Distribution of early warning stations and 2.4 GHz spread-spectrum radio modem transmission (far stations BOTAS, SINANOBA and YAKUPLU data-link modems have been replaced with satellite link in the beginning of the year 2008).

the respective threshold value within a 10 s (selectable) time interval, the respective alarm level is declared.

[7] In early warning system utilizing the direct (engineering) approach, algorithms are based on the exceedance of specified threshold time domain amplitudes. The most used parameters for such system are band-pass filtered PGA and CAV values. The definitions and setting of the triggering threshold levels play major role in the success of such algorithms. The band-pass filtered PGA is an easy and effective parameter for triggering. To account for near-field and far-field strong-ground motions the three components (x, y, z) can be used. Along with the PGA values, another approach, so called CAV was originally proposed in a study sponsored by the *Electric Power Research Institute* (*EPRI*) [1988] as a parameter for determining the damage threshold for engineered structures and anchored industrial grade equipment subjected to earthquake ground motion. In this way the CAV regards the contribution of both the amplitude and the duration of motion. Existence of a very good relationship between the earthquake intensity (EMS' 98) and the CAV is provided by *Böse* [2006]. Originally, the CAV was defined as the sum of the consecutive peak-to-valley distances in the velocity time history. Later on, a modified method of calculating CAV was proposed by *EPRI* [1991] in order to remove the dependence on records of long duration containing low (non-damaging) accelerations. This results in a new parameter called Bracketed Cumulative Average Velocity (BCAV). The method of computing BCAV is based on summation of average velocity (sum of the integration of acceleration a(t) time history) within a time domain where the maximum acceleration exceeds a predetermined acceleration value (typically 0.025 g) in a specific bracketed time (Δt). BCAV is computed by

$$\mathrm{BCAV} = \sum \int_{t_i}^{t_i+\Delta t} |a(t)|dt \quad \text{where} \quad \Delta t = 1 \text{ s}, \qquad \max|a(t)| > 0.025 \text{ g} \tag{1}$$

Recently, instead of classical CAV or BCAV, a new approach, namely BCAV-W, of which details are given by *Alcik et al.* [2006] is planned to use in the IEEW system. In the following part, the definition of BCAV-W is explained.

3. Windowed Bracketed Cumulative Average Velocity (BCAV-W)

[8] On-line early warning automatic triggering systems for building type structures and industrial facilities require some modifications to the definition of BCAV due to the following operational reasons: a) To eliminate the accumulated BCAV values due to different reasons, for examples: high noises, small earthquakes and far field events, b) To adjust the minimum acceleration level which is proposed for nuclear power plants to consider the lower acceleration level for building type structures, c) To identify the short-time earthquake motions with very large peak ground accelerations (near-field impulsive) from long time earthquake motions with lower acceleration level (far-field). For on-line early warning systems, BCAV can be defined for specific window time length (Figure 2). BCAV is to window CAV calculation on a second-by-second basis for a given time history. If the absolute acceleration exceeds 0.025 g at any time (t_i) during each one second interval, CAV, for that second, is calculated and summed. On the other hand, for the modified BCAV method (BCAV-W), the calculation is performed by windowing BCAV calculation on a broader window length (W) basis. In our case, window length is selected as 8 seconds, and summation in the equation (2) is performed from the first bracketed time (W = 1) to the eighth. The specific window-based BCAV can be called BCAV-W and computed as follows;

$$\mathrm{BCAV-W} = \sum_{W=1}^{\text{win length}} \int_{t_i}^{t_i+\Delta t} |a(t)|dt \quad \text{where} \quad \Delta t = 1 \text{ s}, \qquad \max|a(t)| > \text{min acc. level} \tag{2}$$

The optimum length of this window and bracket time and their effects on the BCAV values for different earthquake-time-history records will be examined in further studies. In this study, the behavior of BCAV with 8-second window length (BCAV-W8), 1-second bracket time and 3 mg for minimum acceleration level are investigated for the Marmara region. We selected 169 records from 43 earthquakes with

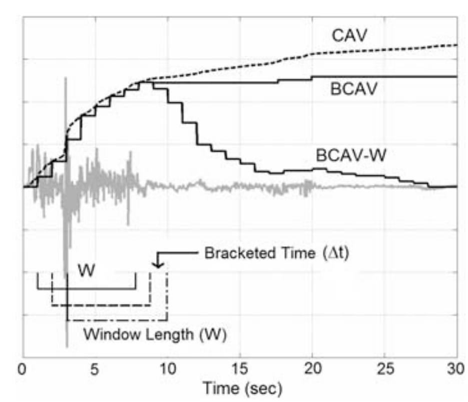

Figure 2. Graphical definitions of CAV, BCAV and BCAV-W [*Alcik et al.*, 2006].

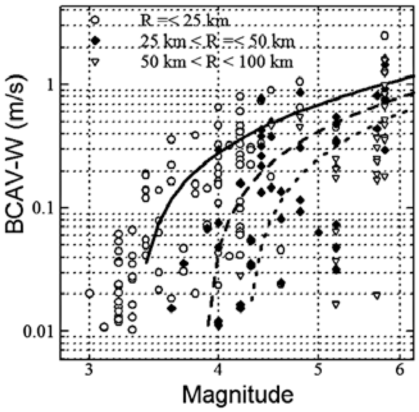

Figure 3. The behavior of BCAV versus local magnitude for different epicentral distance (R) ranges with 8 seconds window length (BCAV-W8), 1 second bracketed time and 3 mg for minimum acceleration level. Totally 169 records from 43 earthquakes with both epicentral distances and focal depths are less than 100 km and 25 km, respectively, were used.

both epicentral distances and focal depths are less than 100 km and 25 km, respectively, from the earthquake catalogue prepared by *Kalafat et al.* [2007]. The relation between BCAV-W8 and local magnitude for three epicentral distance ranges are shown in Figure 3. It should be noted that the data are not classified related to soil velocities.

4. Conclusion

[9] The devastating earthquakes of Kocaeli and Düzce in 1999 have initiated the development of a real-time earthquake information system in Istanbul: IERREWS. As a part of IERREWS, the IEEW system, with an algorithm based on the exceedance of specified threshold time-domain amplitude of PGA and CAV levels, is implemented in 2002. In addition to the current 12 Hz. low-pass filtered PGA values, CAV values can also be used. When any CAV (computed for only those 1 second intervals where PGA is greater than 0.03 m/s^2) on any channel exceeds the first threshold CAV value, it will be considered a vote. Whenever system has votes from at least 3 stations within selectable time interval of (5 s or 10 s) after the first vote, the system will declare the first alarm. The IEEWs has three selectable alarm levels. Since some modifications to the BCAV are required, a new approach, namely BCAV-W, is suggested and its definition is presented. Using the data set from the Marmara Region, rational threshold levels related to new-bracketed CAV window approach are determined. As a result, the bracketed CAV window values that will be put into practice are accepted as to be 0.20, 0.40 and 0.70 m/s for three alarm levels, respectively. In conclusion, the use of PGA together with bracketed CAV window in seismic early warning purpose will prevent early warning systems from producing false alarm.

[10] For improving current early warning system capability, another early warning algorithms, such as τ_p^{max} [*Shieh et al.*, 2008], τ_c and Pd methods [*Wu and Kanamori*, 2008] are also under consideration. In this connection, empirical relationships related to those methods for the Marmara Region should be derived. This type regression-based approaches for seismic early warning will become effective especially for close-in sites where warnings are most needed and are suitable to address the problem of real-time prediction in areas and cities with extremely little warning times, such as in the case of Istanbul, Turkey.

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References

Alcik, H., Y. Fahjan, and M. Erdik (2006), Analysis of triggering algorithms for direct (engineering) early warning systems, paper 1198 presented at the First European Conference on Earthquake Engineering and Seismology, Geneva, Switzerland, 3–8 Sept.

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

Böse, M. (2006), Earthquake early warning for Istanbul using artificial neural networks, Ph.D. thesis, Fakultät für Phys., Univ. ät Karlsruhe, Karlsruhe, Germany.

Böse, M., F. Wenzel, and M. Erdik (2008), PreSEIS: A neural network-based approach to earthquake early warning for finite faults, *Bull. Seismol. Soc. Am.*, *98*, 366–382.

Electric Power Research Institute (EPRI) (1988), A criterion for determining exceedance of the operating basis earthquake, *Rep. NP-5930*, Electr. Power Res. Inst., Palo Alto, Calif.

Electric Power Research Institute (EPRI) (1991), Standardization of the cumulative absolute velocity, *Rep. TR-100082*, Electr. Power Res. Inst., Palo Alto, Calif.

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

Erdik, M., M. Demircioğlu, K. Sesetyan, E. Durukal, and B. Siyahi (2004), Earthquake hazard in Marmara region, Turkey, *Soil Dyn. Earthquake Eng.*, *24*, 605–631.

Espinosa-Aranda, J., A. Jimenez, G. Ibarrola, F. Alcantar, A. Aguilar, M. Inostroza, and S. Maldonado (1995), Mexico City seismic alert system, *Seismol. Res. Lett.*, *66*, 42–53.

Kalafat, D., Y. Gunes, M. Kara, P. Deniz, K. Kekovali, H. S. Kuleli, L. Gulen, M. Yilmazer, and N. M. Ozel (2007), *A Revised and Extented Earthquake Catalogue for Turkey Since 1900 (M $\geq$ 4.0)*, Bogazici Univ. Press, Istanbul, Turkey.

Nakamura, Y. (1988), On the urgent earthquake detection and alarm system (UrEDAS), *Proc. Ninth World Conf. Earthquake Eng.*, *VII*, 673–678.

Olivieri, M., R. M. Allen, and G. Wurman (2008), The potential for earthquake early warning in Italy using ElarmS, *Bull. Seismol. Soc. Am.*, *98*, 495–503.

Shieh, J.-T., Y.-M. Wu, and R. M. Allen (2008), A comparison of τ_c and τ_p^{max} for magnitude estimation in earthquake early warning, *Geophys. Res. Lett.*, *35*, L20301, doi:10.1029/2008GL035611.

Wenzel, F., M. C. Oncescu, M. Baur, and F. Fiedrich (1999), An early warning system for Bucharest, *Seismol. Res. Lett.*, *70*, 161–169.

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

Wu, Y. M., J. K. Chung, T. C. Shin, N. C. Hsiao, Y. B. Tsai, W. H. K. Lee, and T. L. Teng (1999), Development of an integrated seismic early warning system in Taiwan—Case for Hualien earthquakes, *Terr. Atmos. Oceanic Sci.*, *10*, 719–736.

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