Ground Shaking Prediction for Earthquake Early Warning

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SUMMARY:
Earthquake early warning (EEW) system provides a few seconds to tens of seconds of warning time for impending ground motions due to a large earthquake and allows for mitigation measures in few seconds. A method for estimating the imminent S-wave ground shaking (PGA, PGV, and PGD) from the initial P-wave is developed. It can be applied to on-site warning directly. Also we present a method to continuous evaluated ground motion maps using the result of estimated value.

Keywords: Earthquake early warning, Ground Shaking Prediction

1. GENERAL INSTRUCTIONS

Earthquake early warning (EEW) system can estimate some seismic parameters and earthquake damage quickly and reliable, based on the real-time seismic monitoring instruments, and give the alarm information before the strong shaking hits a given target. It is a new means for earthquake disaster reduction and mitigation. Now some EEW systems have been implemented or under testing for specific facilities or national range in many countries, and some of them had got the disaster reduction effectiveness (Allen *et al.*, 2009; Satriano *et al.*, 2011). For example, the Earthquake Early Warning System implemented by Japan Meteorological Agency (Allen *et al.*, 2009; Kamigaichi, 2004), three systems the Elarms, Virtual Seismologist and PreSEIS are currently being tested in California (Allen *et al.*, 2009). Some other countries and regions, such as Mexico (Espinosa-Aranda *et al*., 1995; Suarez, 2009), Italy (Satriano *et al.*, 2010), Romania (Böse, 2007), Chinese Taiwan (Wu *et al.*, 2002; Wu *et al.*, 2008) and Turkey (Alcik *et al.* 2009) and also run or test the system actively. China is one of the countries which suffer the most serious earthquake disaster in the world. In order to cope with the attack on the society by future strong earthquakes, China also plans to implement the EEW system to mitigate the earthquake losses as much as possible. Experimental system has been developed and installed in Fujian rejoin and Beijing Capital Area. With the perfection of the system, the pilot areas will be expanded.

The EEW system is broadly classified into onsite warning and regional warning (Satriano *et al.*, 2011). No matter what kind of practice, the ground shaking prediction for the impending ground motions not yet reached a certain area is very important. After the earthquake occurred, if we can roughly estimate the size to reach the ground motion, combined with the reality of engineering facilities, the potential damage can be estimated, and then decide what measures will be done. The main predicted parameters include PGA, PGV, PGD, and intensity (Ma, 2008).

After an earthquake, the stations with the distance of hypocenter distance get the records of ground motion one by one. The following methods can be considered to predict the ground motion. If earthquake parameters have got, ground motion attenuation relations can be used to get the ground motion map directly. It should be noted that, because the location and magnitude of earthquake early warning is rough, its error will be brought into the result. If some stations near the source get the limited initial P waves, they can be used to estimate the follow-up of ground motion and used for on-site warning directly. The estimated ground motion also can be used to predict the ground motion map for early warning. In this paper we develop a method for estimating the imminent S-wave ground shaking (PGA, PGV, and PGD) from the initial P-wave. It can be applied to on-site warning directly. Also we present a method to continuous evaluated ground motion maps using the result of estimated value and can also be used based on a regional early warning of seismic observation network.

2. GROUND SHAKING PREDICTION USING INITIAL P-WAVE

With the propagation of seismic waves after the earthquake, according to the focal distance, the stations receive the ground motion one by one. The records carry the source information, such as the phase arriving time carry the source location information, the amplitude and spectrum also carry the characteristics and information of the source and the earth medium.

Ma *et al.* (2008b) has proposed a methodology to determinate the magnitude continually for every second after 1sec of the nearest station P-wave arrival by using the seismic network records. Three predomination period parameters and three amplitude parameters of initial P-wave in four different frequency band records are used to model the nonlinear relation between the magnitude using neural network is trained and the result shows that the method is effective and reliable to determinate the magnitude for EEW. In this paper we apply the same method of application of seismic records of P wave initial segment to continue to estimate that follow-up ground motion (PGA, PGV and PGD).

2.1 Datasets

In the present study we used borehole records from Strong Motion Seismograph networks (Kiban Kyoshin network, Kik-net) of Japan (http://www.kyoshin.bosai.go.jp/kyoshin/). The borehole was design so that it penetrates the sediment and reaches to rock. In order to meet the SNR requirements, the selection criteria was Mj>4.0 and the records at the hypocentral distance that satisfied the following Eqn.2.1.

$$\log R \leq 0.86 + 0.17 M_j \qquad (2.1)$$

A total of 141 events and 1018 three-component records occurred during the period from 1997 to 2007 were used for this study.

2.2 Method

The method is broadly divided into the following six steps.

1. The P-arrival is detected using the short-term-average/short-term-average (STA/LTA) and Akaike Information Criterion (AIC) method from the strong motion records automatically (Ma *et al.*, 2012).

2. Consider the different frequency bands of the records, the acceleration records is simulated by various natural periods' single-degree-of-freedom system response to acceleration, velocity and displacement respectively (the natural period is 1s, 3s, 5s, and 10s respectively, damping ratio is 0.707).

3. Three period parameters and three amplitude parameters are calculated at P-wave record segments t_i (i = 1,2, .., 10) (the length of P-wave is concerned with hypocentral distance) in different frequency bands(Ma *et al*., 2008).

4. Two-layer feed-forward artificial neural network (ANN) is applied. Three period parameters and three amplitude parameters of P-wave segment for four different frequency band and the focal distance

are as input, the total input parameters is 25. The PGA, PGV, and PGD is as output respectively.

5. The early stopping training functions is used in the neural networks training to avoid the overfit the data. 1018 records are random divided into three subsets. The first subset of 60% datum is the training set, which is used for computing the gradient and updating the network weights and biases. The second subset of 20% datum is the validation set. The error on the validation set of 20% datum is monitored during the training process.

6. Trained artificial neural network prediction model is used to get imminent S-wave ground shaking (PGA, PGV, and PGD) from the initial P-wave

2.3 Result

Application to the above methods, trained artificial neural network prediction model for PGA, PGV, and PGD are obtained for different P-wave segments t_i (i = 1,2, .., 10).The results of the prediction of PGA, PGV and PGD within 3s of the P-wave arrival are shown in Fig.2.1-3. And the results within every second point of the P-wave arrival are shown in Table 2.1.
From Tab.2.1 we can get that the standard deviation of predicted logarithm peak value of imminent S-wave ground shaking is about 0.3, that is the ratio of predicted and actual values is between $10^{\pm 0.3}(0.5 \sim 2)$, it has to meet earthquake early warning needs. Only some of the results of PGA, PGV and PGD are showne in this paper, to apply the same method we also can predict the intensity or response spectra parameters.

Table 2.1 the standard deviation of predicted logarithm peak value using for different P-wave segments t_i

P-wave segments t_i	1s	2s	3s	4s	5s	6s	7s	8s	9s	10s
log(PGA)	0.334	0.310	0.274	0.265	0.336	0.271	0.263	0.264	0.254	0.293
log(PGV)	0.360	0.332	0.320	0.305	0.293	0.278	0.280	0.279	0.277	0.281
log (PGD)	0.462	0.413	0.402	0.397	0.324	0.325	0.326	0.323	0.313	0.351

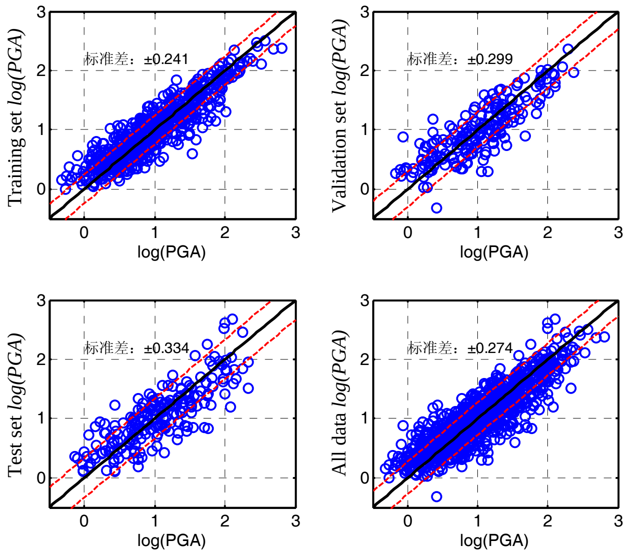

Figure 2.1 The results of PGA using the ANN within 3s of the P-wave arrival

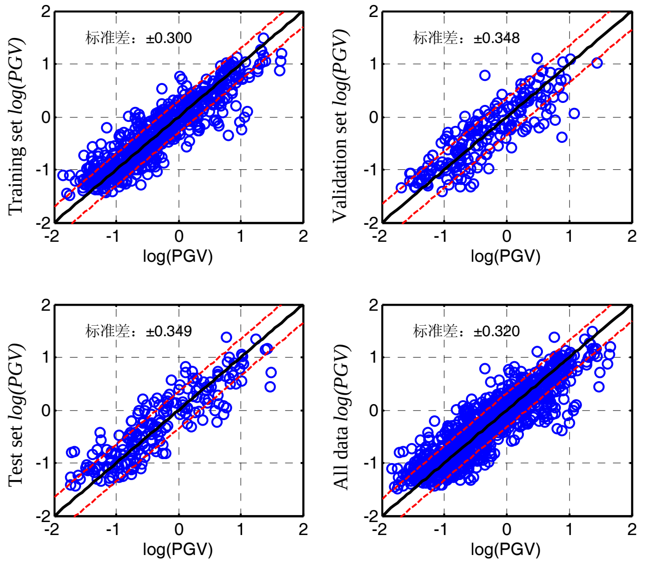

Figure 2.2 The results of PGV using the ANN within 3s of the P-wave arrival

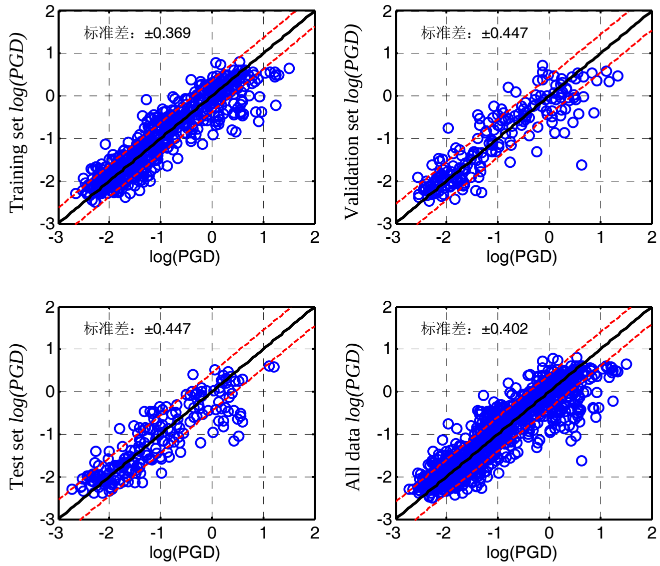

Figure 2.3 The results of PGD using the ANN within 3s of the P-wave arrival

3. GROUND MOTION MAP PREDICTION

3.1 Ground Motion Attenuation Relations

The above methods can only be used in on-site warning to get the predicted imminent S-wave ground shaking at the station. If we got earthquake parameter, ground motion attenuation relations can be used to get the ground motion map directly:

$$\log Y = f(M, R) = a + bM + c\log(R + R_0) \qquad (3.1)$$

here M is magnitude and R is the hypocentral distance., Y is the ground motion parameter (PGA, PGV, or PGD).

It should be noted that, because the location and magnitude of earthquake early warning is rough, its error will be brought into the result. Also, it is only a general fitting of the ground motion attenuation, unable to take into account the personality of each earthquake.

3.2 Ground Motion Map

Assuming that there is already one or more than one station which get the P-wave records (Fig2.1), predicted imminent S-wave ground shaking at every station can be got. According to the geometry of the seismic stations distribution, near-source stations also may have got the S-wave peak. The ground motion estimates can be transformed into that using Multiple-station records draw shake map.
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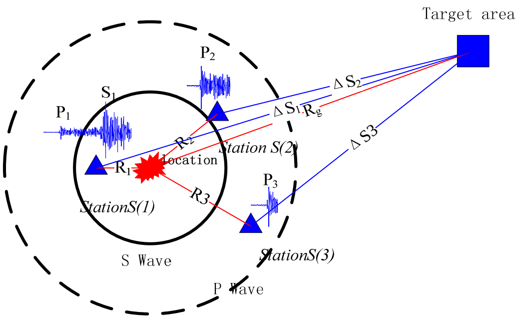


Figure 3.1. Schematic plot for ground motion prediction for any field

For the earthquake location and station distribution in Figure 2.1, assuming that there is already one or more than one station to get the P-wave records, and the predicted S-wave peak value (PGA, PGV, or PGD) donated by Y_i, S(i) is the *i*-th station that P wave has reached, R_i is the hypocentral distance for the *i*-th station. Assume that Y_i, meet the existing attenuation relations:

$$\log Y_i = a + bM + c\log(R_i + R_0) \tag{3.2}$$

Ground motion prediction for any target field and hypocentral distance donated by Y_g and R_g respectively and also meets attenuation relations Eq.3.1, we can get:

$$\log Y_g = a + bM + c\log(R_g + R_0) \tag{3.3}$$

For the same earthquake seismic parameters are the same, the above two equations subtraction, there are:

$$Y_g = Y_i \left(\frac{R_g + R_0}{R_i + R_0} \right)^c \tag{3.4}$$

The hypocentral distance of *i*-th station donated by ΔS_i and the k is the number of stations record the P-wave, if k>=1, the weight w_i contribution of each station on the target area can use the equation as follows:

$$Y_g = \sum_{i=1}^{k} W_i Y_{gi} \tag{3.5}$$

$$W_i = \frac{1}{(\Delta S_i)^2} \Big/ \sum_{i=1}^{k} \frac{1}{(\Delta S_i)^2} \tag{3.6}$$

It can be seen from the above, the magnitude is not used to predict ground motion for an earthquake. With the increase of the record information, the ground shaking map can be continuously updated. If the area is divided into grids, each grid above formula can be obtained throughout the region of ground motion maps.

3.3 Example

On October 23, 2004, an earthquake (Mw=6.6, Mj=6.8) occurred in Mid Niigata Pref., Honshu, Japan. The depth of hypocenter is 14km approximately. After 4.1 second of the earthquake occurred, the nearest KiK-net station NIGH12 received the 1sec P-wave and we can get the first predicted ground shaking map, and the S-wave was not arrive to the ground at that moment.

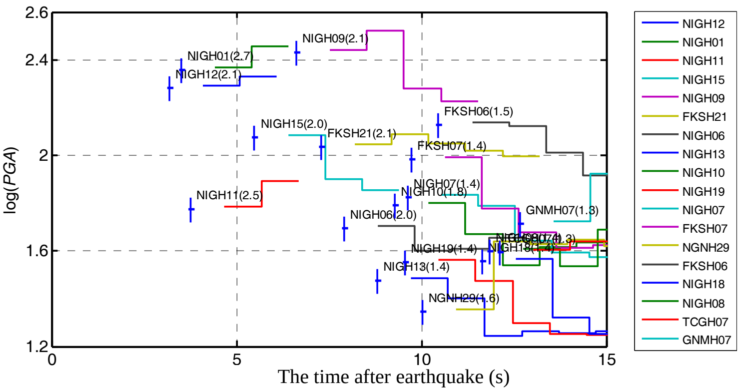
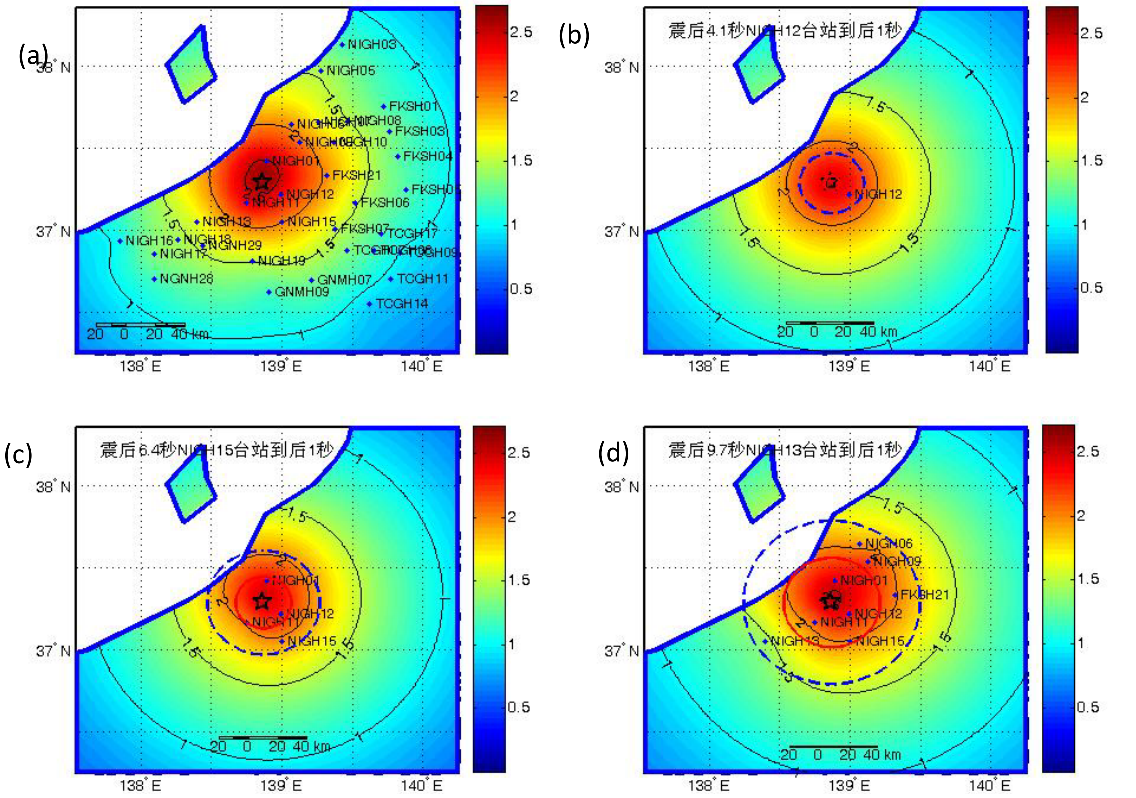


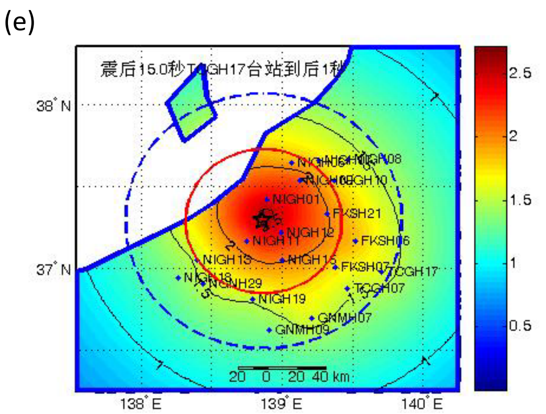
Figure 3.2 Continual Ground Shaking Prediction using the initial P-wave segments
(+for the P-arrival time, Values in brackets for the final value, and lines for the predicted values)

Table 3.1 Continual Ground Shaking Prediction using the initial P-wave segments

No	Station	hypocentral distance (km)	P Travel time (s)	Actual log(*PGA*)	Ground Shaking Prediction log(*PGA*)									
					1s	2s	3s	4s	5s	6s	7s	8s	9s	10s
1	NIGH12	18.1	3.1	2.1	2.3	2.3	-	-	-	-	-	-	-	-
2	NIGH01	20.0	3.4	2.7	2.4	2.5	-	-	-	-	-	-	-	-
3	NIGH11	21.5	3.7	2.5	1.8	1.9	-	-	-	-	-	-	-	-
4	NIGH15	31.6	5.4	2.0	2.1	1.9	1.9	-	-	-	-	-	-	-
5	NIGH09	38.2	6.5	2.1	2.4	2.5	2.3	2.2	-	-	-	-	-	-
6	FKSH21	42.1	7.2	2.1	2.0	2.1	2.0	2.0	2.0	-	-	-	-	-
7	NIGH06	45.8	7.8	2.0	1.7	1.6	1.6	1.7	1.6	-	-	-	-	-
8	NIGH13	51.0	8.7	1.4	1.5	1.4	1.2	1.3	1.3	1.3	-	-	-	-
9	NIGH10	53.8	9.2	1.8	1.8	1.7	1.5	1.6	1.6	1.6	-	-	-	-
10	NIGH19	55.4	9.5	1.4	1.6	1.5	1.3	1.3	1.2	1.2	-	-	-	-
11	NIGH07	55.8	9.5	1.4	1.8	1.8	1.6	1.6	1.6	1.5	-	-	-	-
12	FKSH07	56.4	9.6	1.4	2.0	1.8	1.7	1.6	1.6	1.6	1.5	-	-	-
13	NGNH29	58.2	9.9	1.6	1.4	1.6	1.6	1.6	1.6	1.6	1.6	-	-	-
14	FKSH06	60.7	10.4	1.5	2.1	2.1	2.0	1.9	1.9	1.9	1.8	-	-	-
15	NIGH18	67.6	11.5	1.4	1.6	1.3	1.3	1.3	1.3	1.3	1.2	1.2	-	-
16	NIGH08	68.8	11.8	1.4	1.6	1.5	1.7	1.7	1.6	1.6	1.6	1.5	-	-
17	TCGH07	70.4	12.0	1.3	1.6	1.6	1.5	1.4	1.4	1.4	1.4	1.3	-	-
18	GNMH07	73.6	12.6	1.3	1.7	1.9	1.8	1.7	1.7	1.7	1.6	1.6	1.5	-
19	GNMH09	75.7	12.9	0.9	1.6	1.5	1.2	1.2	1.2	1.2	1.1	1.1	1.0	-
20	TCGH17	81.7	14.0	1.1	1.9	2.0	1.7	1.7	1.7	1.7	1.6	1.6	1.5	1.5
21	TCGH08	83.7	14.3	1.2	1.9	1.9	1.7	1.7	1.7	1.6	1.6	1.5	1.5	1.5
22	NIGH17	84.7	14.5	1.5	1.3	1.3	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
23	NIGH05	85.4	14.6	1.6	1.4	1.4	1.4	1.4	1.4	1.4	1.3	1.3	1.3	1.3
24	FKSH04	86.4	14.8	1.1	0.9	1.3	1.3	1.1	1.2	1.1	1.2	1.2	1.2	1.2

No	Station	hypocentral distance (km)	P Travel time (s)	Actual log(*PGA*)	Ground Shaking Prediction log(*PGA*)									
					1s	2s	3s	4s	5s	6s	7s	8s	9s	10s
25	FKSH03	86.8	14.8	1.4	1.6	1.7	1.6	1.6	1.5	1.4	1.4	1.4	1.4	1.4
26	FKSH05	90.0	15.4	1.2	1.8	1.7	1.6	1.6	1.6	1.6	1.5	1.5	1.5	1.5
27	FKSH01	91.9	15.7	1.1	1.7	1.6	1.3	1.2	1.2	1.2	1.1	1.1	1.1	1.1
28	NGNH28	95.2	16.3	1.1	1.4	1.3	1.4	1.3	1.4	1.3	1.3	1.3	1.2	1.2
29	TCGH09	99.2	16.9	0.8	1.9	1.6	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.4
30	NIGH16	99.4	17.0	0.9	1.5	1.5	1.4	1.4	1.4	1.3	1.3	1.2	1.2	1.2
31	TCGH11	104.0	17.8	0.9	1.8	1.7	1.7	1.6	1.6	1.6	1.5	1.4	1.4	1.3
32	TCGH14	106.6	18.2	0.7	1.5	1.6	1.5	1.5	1.5	1.5	1.4	1.4	1.3	1.3
33	NIGH03	106.7	18.2	1.2	1.6	1.9	1.5	1.4	1.3	1.3	1.3	1.2	1.2	1.2





(a) using all final records of 33 stations nearest epicenter;
(b) only the nearest station (NIGH12) get one second long P-wave (4.1 second after the earthquake);
(c) the 4th station (NIGH15) get one second long P-wave (6.4 second after the earthquake);
(d) the 8th station (NIGH13) get one second long P-wave (9.7 second after the earthquake);
(e) the 20th station (NIGH17) get one second long P-wave (15 second after the earthquake);

Figure 3.3. Continual Shaking Map Prediction (Distribution of *log(PGA)*)
(Red solid line circle: S wave front; Blue dotted line: P wave front)

5. DISCUSSION AND CONCLUSIONS

We have developed a method to estimate the imminent ground shaking (PGA, PGV, PGD) for every second after P-wave arrived based on ANN. It can be applied to on-site warning directly. Also we present a method to continuous evaluated ground motion maps using the result of estimated value exist station.

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REFERENCES

Alcik H, Ozel O, Apaydin N, Erdik M. (2009). A study on warning algorithms for Istanbul earthquake early warning system. *Geophysical Research Letters*, 36.

Allen R M, Gasparini P, Kamigaichi O, Bose M.(2009). The status of earthquake early warning around the world: an introductory overview . *Seismol. Res. Lett.*, **80(5)**:682–93.

Böse M, Ionescu C, Wenzel F. (2007). Earthquake early warning for Bucharest, Romania: Novel and revisited scaling relations. *Geophysical Research Letters,* **34**, L07302.

Espinosa-Aranda J, Jimenez A, Ibarrola G, et al. (1995). Mexico City seismic alert system. *Seism. Res. Lett.*, **66(6):**42–53.

Hsiao N C, Wu Y M, Shin T C, et al. (2009). Development of earthquake early warning system in Taiwan. *Geophys. Res. Lett.*, **36**:L00B02,doi:10.1029/2008GL036596.

Kamigaichi O. (2004). JMA earthquake early warning[J].*Jpn. Assoc. Earthquake. Eng.*, **4(3)**:134–137.

MA Q. (2008). Study and Application on Earthquake Early Warning (in Chinese) [Ph. D. theses]. *Harbin: Institute of Engineering Mechanics, China Earthquake Administration*.

MA Q., JIN X. (2008). Continual Determination of Magnitude for Earthquake Early Warning, 09-01-0180, *14th World Conference on Earthquake Engineering*, Beijing.

MA Q., JIN X., LI S.Y., CHEN F. W., LIAO S.R., WEI Y. X. (2012). Automatic P-arrival Detection for Earthquake Early Warning, *Chinese J. Geophys.* (in Chinese), (in publish).

Nakamura Y. (2004). UrEDAS, URGENT EARTHQUAKE DETECTION AND ALARM. *13th World Conference on Earthquake Engineering*, Vancouver, B.C., Canada:.

Satriano C., Elia L., Martino C., Lancieri M., Zollo A., Iannaccone G. (2010). PRESTo, the earthquake early warning system for Southern Italy:concepts, capabilities and future perspectives.*Soil. Dyn. Earthquake. Eng.* , doi:10.1016/j.soildyn.2010.06.008.

Satriano C, Wu Y, Zollo A, et al. Earthquake early warning: Concepts, methods and physical grounds. Soil Dynamics and Earthquake Engineering, 2011, **31(2)**: 106-118.

Suarez G, Novelo D, Mansilla E. (2009). Performance evaluation of the seismic alert system (SAS) in Mexico City: a seismological and a social perspective. *Seismol. Res. Lett.*, **80(5)**:707–16,doi:10.1785/gssrl.80.5.707.

Wu Y M, Teng T L. (2002). Avirtual sub-network approach to earthquake early warning. *Bull. Seism. Soc. Am*., **92(5)**:2008–2018.

Wu Y M, and Kanamori H. (2008). Development of an Earthquake Early Warning System Using Real-Time Strong Motion Signals, *Sensor* , **8**:1-9.