ALGORITHM "MAP OF EXPECTED EARTHQUAKES" (MEE): RESULTS OF THREE DECADES OF TESTING AND LATEST FINDINGS

Zavyalov A. D.

Schmidt Institute of Physics of the Earth, Russian Academy of Sciences,
Moscow, Russia
e-mail: zavyalov@ifz.ru

Abstract. The Map of Expected Earthquakes (MEE) algorithm was suggested in the mid-1980s by G.A. Sobolev, T.L. Chelidze, L.B. Slavina, and A.D. Zavyalov. Over the last more than 30 years, the algorithm has been tested in a variety of seismically active regions all over the world, including the Caucasus, Kamchatka, the Kopet Dag, the Kyrgyz Republic, Southern California, Northeast and Southwest China, Greece, West Turkey, the Kuril Islands, and New Zealand. The average predictive effectiveness for these regions was $J_{MEE} = 2.56$ and 3.82, with conditional probability value $P(D_1|K) = 70$ % and 90 %, respectively, selected as an alarm level. This being the case, 68 % and 41 % of predicted earthquakes occurred in the zones with these levels of conditional probability; the area of alarm zones was 30 % and 14 % of the total area of observations, respectively.

The most recent paper was the first to use the MEE medium-term earthquake prediction algorithm to develop maps of expected earthquakes in a classical area with a transient seismic regime, namely the Koyna–Warna reservoir site (India). The local earthquake catalogue for this area, covering the period of time from 1996 to 2012 (approximately 17 years) and including 4500 earthquakes with $M_L = 0$–6.5 magnitudes that occurred in the depth range of H =0-20 km, was used as the database for this work. Linear dimensions of the seismic area are 40×60 km.

A series of 42 expected earthquake maps was developed for the Koyna–Warna area, from 1 July 2002 till 1 October 2012, with 3-month step and 2-year prediction periods for each map. The findings of using the MEE algorithm in a classical area with a transient seismic regime for the first time were very encouraging. They showed that its prediction reliability was quite high and equal to J_{MEE} =2.76. Zones with conditional probability levels $P(D_1|K) \geq 90\%$ experienced 56.3 % of all earthquakes with $M_L \geq 4.0$. The alarm area was 20.4±8.4% of the total area of observations. The MEE algorithm was particularly efficient in predicting the largest earthquakes in the Koyna–Warna area that occurred during the retrospective prediction period. At a later stage, more accurate adjustment of algorithm parameters may improve the overall prediction reliability.

Therefore, integral predictive reliability estimates obtained when the MEE algorithm was used for the Koyna–Warna reservoir site are close to the average values of these parameters for all previous seismically active regions. These findings, firstly, may be considered proof of the flexibility of the proposed algorithm. And, secondly, this example can be useful for medium-term earthquake prediction in other seismoactive areas around high dams.

Keywords: earthquake prediction, map of expected earthquakes, algorithm, Koyna-Warna reservoirs

Introduction

In the mid-1980s, an informal research team called the Quick-Look Comparative Seismic Analysis (QCSA) Team was formed at the Institute of Physics of the Earth (IPE) in the USSR Academy of Sciences. The team was headed by G.A. Sobolev and had no permanent members. At different times, the members of the team were:

From IPE of the Russian Academy of Sciences (RAS): *Gennady A. Sobolev, Lidia B. Slavina, Alexey D. Zavyalov, Elizaveta N. Sedova, Evgeny A. Rogozhin, Andrey A. Nikonov, Timur T. Tagizade.*

Aleksey D. Zavyalov, Dr. Sci., Head of Seismic Hazard Laboratory, Schmidt's Institute of Physics of the Earth, Russian Academy of Sciences; email: zavyalov@ifz.ru

From the Institute of Geophysics (Georgia): *Tamaz L. Chelidze, Tamaz Pilishvili, Rusiko Khelashvili, Vano E. Nikoladze, Lali Kakhiani, Lali Labadze, Yury M. Kolesnikov.*

The task of the team was to develop methodology for mapping areas where major earthquakes are most likely to occur, using time and space distributions of various geological and geophysical data. After several years of work, the team developed an algorithm that was later called as the Map of Expected Earthquakes (MEE).

By the earthquake prediction algorithm we shall mean a sequence of actions to distinguish unique characteristics or abnormal changes in various geological and geophysical fields, and study and analyze them all to determine the location, intensity, and time of an earthquake.

The MEE algorithm is based on the concept of destruction of the geological environment as a self-similar and self-organized system of different-scale rock blocks. Based on the kinetic concept of strength in solids, the authors developed images of abnormal behaviour for different seismological parameters (precursors) before major ($M \geq 5.5$) earthquakes. The MEE algorithm uses the principle of space-time scanning of the earthquake catalogue within the seismically active region under study. Using the Bayesian approach, maps of conditional probability distribution $P(D_1|K)$ for a potential major earthquake in each space-time cell were calculated. These maps were called the Maps of Expected Earthquakes.

Over the last more than 30 years, the algorithm has been tested in a variety of seismically active regions all over the world, including the Caucasus, Kamchatka, the Kopet Dag, the Kyrgyz Republic, Southern California, Northeast and Southwest China, Greece, West Turkey, the Kuril Islands, and New Zealand. The average predictive effectiveness for these regions was $J_{MEE} = 2.56$ and 3.82, with conditional probability value $P(D_1|K) = 70$ % and 90 %, respectively, selected as an alarm level. This being the case, 68 % and 41 % of predicted earthquakes occurred in the zones with these levels of conditional probability; the area of alarm zones was 30 % and 14 % of the total area of observations, respectively.

This paper also presents the results of developing maps of expected earthquakes for the Koyna–Warna reservoir site. The site is interesting for the reason that it was considered aseismic prior to the construction of the Koyna Dam in the north and reservoir filling (started in 1961); therefore, no instrumental seismic observations were conducted in the area. However, on 10 December 1967 a devastating earthquake with $M_{\mathrm{L}} = 6.5$ hit the area. The earthquake later named the Koyna Earthquake was a classic example of an earthquake triggered by human activity. The same happened again when the Warna Dam was constructed (to the south of the Koyna Dam) and its reservoir was filled (filling started in 1985). Therefore, seismic activity has been observed in the region for almost 50 years and seismic observations have been underway.

The Koyna–Warna area has a transient seismic regime, with such important features as short duration of the observation period, a small area under study and, therefore, a small number of seismic events in the catalogue. During our work, we managed to overcome the challenges associated with a relatively short period of instrumental seismological observations and a small number of earthquakes in the catalogue. This work for Koyna–Warna area was done for the first time. Before that, maps of expected earthquakes were developed only for seismically active regions with pronounced tectonic activity, such as continental margins, island arcs, subduction zones, etc.

1. Examples of MEE Algorithm Applications in Various Regions

Kamchatka. The regional earthquake catalogue for 1962–2012, prepared by the Kamchatka Branch of the Geophysical Survey of RAS was used to compile maps of expected earthquakes in Kamchatka. The catalogue includes almost 180 thousand earthquakes with energy classes $K = 0$–16.1 that occurred in the depth range of $H = 0$–701 km. $K_{\mathrm{rep}} = 9.5$ is the representative energy class of earthquakes. $H = 0$–100 km was selected as the hypocenter depth range for earthquakes included in MEE calculations. Approximately 16300 events were included in the working catalogue of representative earthquakes with $K_{\mathrm{rep}} \geq 9.5$ that occurred in the depth range of $H = 0$–100 km during 1962–2012. The energy class of major earthquakes, i.e. prediction targets, was selected equal to $K_{\mathrm{pr}} \geq 13.5$ ($M_{\mathrm{pr}} \geq 6.0$).

Fig. 1 shows one of the maps of expected earthquakes in Kamchatka with the prediction

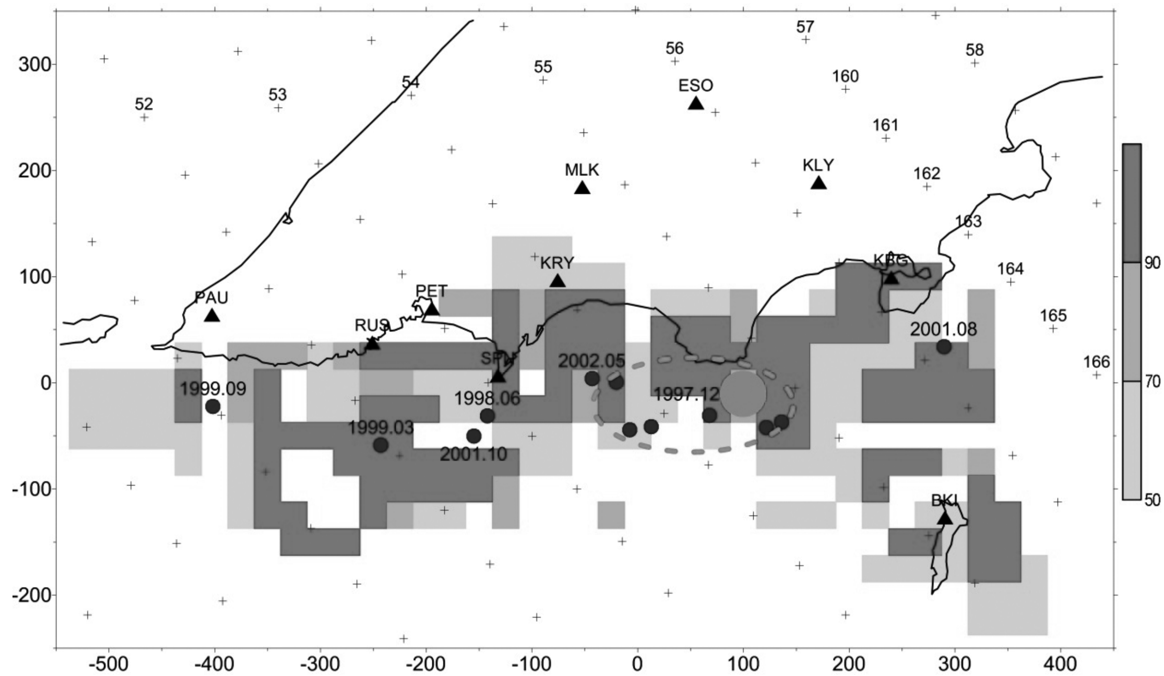


Figure 1. Map of expected earthquakes (map of conditional probability distribution) in Kamchatka for the period from 1 January 1997 to 31 December 2002. The map shows epicenters of earthquakes and their groups with $K_{pr} \geq 13.5$ that occurred during the MEE validity period (6 years). The size of circles is proportional to the length of rupture in the earthquake source on the map scale. The dashed ellipse indicates a group of earthquakes that occurred on 5–7 December 1997. The legend in conditional probability terms is shown on the right. The dimensions of a square elementary cell are 25×25 km. The axes of Cartesian coordinates are given in kilometers

period from 1 January 1997 to 31 December 2002 (6 years). All earthquakes with $K_{pr} \geq 13.5$ that occurred during this time interval are plotted on the map. Most number of these earthquakes originated in zones where levels of conditional probability were higher than 50 %. The results of the retrospective prediction for Kamchatka for the entire period of observations are summarized in Table 1. The total number of earthquakes with the corresponding energy range is given in brackets.

The Kuril Islands. Fig. 2 shows an example of a map of expected earthquakes for the Kuril Islands area with the prediction period from 1 October 2006 to 30 September 2010 (4 years) covering the series of Simushir earthquakes in November 2006 ($M = 8.3$) and January 2007 ($M = 8.2$). In this case, we used the data from the regional earthquake catalogue for 1962–2009, prepared by the Sakhalin Branch of the Geophysical Survey of RAS for calculation purposes. $K_{rep} = 9.5$ is the representative energy class of earthquakes. H = 0–100 km was selected as the hypocenter depth range for earthquakes included in MEE calculations. Approximately 18 thousand events were included in the working catalogue of 1962–2009. The energy class of major earthquakes, i.e. prediction targets, was also selected equal to $K_{pr} \geq 13.5$ ($M_{pr} \geq 6.0$). As can be seen from Fig. 2, most number of the earthquakes $K_{pr} \geq 13.5$ originated in the zones where levels of conditional probability were higher than 50 %.

New Zealand. The regional earthquake catalogue for 1980–2010, compiled by GeoNet Project (http://www.geonet.org.nz/), with a total number of 400 thousand seismic events, was used for MEE calculations. According to preliminary analysis, the representative magnitude for this catalogue is $M_{rep} = 3.5$ for the entire period of observations and for the most part of the seismically active region. H = 0–50 km was selected as the depth interval. The working catalogue included almost 20 thousand representative earthquakes. Earthquakes with magnitudes $M_{pr} \geq 5.5$ were the prediction target. Fig. 3 shows one of the maps of expected earthquakes in New Zealand with a prediction

Table 1. Retrospective Prediction Results for the MEE Algorithm in Kamchatka

Energy class range	Conditional probability level, $P(D_1\|K)$		
	50 %	70 %	90[%
$K \geq 15.5$	1 (2)	1 (2)	**1 (2)**
$14.5 \leq K < 15.5$	5 (7)	4 (7)	**2 (7)**
$13.5 \leq K < 14.5$	38 (46)	35 (46)	**26 (46)**
Total:	44 (55)	40 (55)	**29 (55)**
J_{MEE}	2.30	3.17	**3.27**

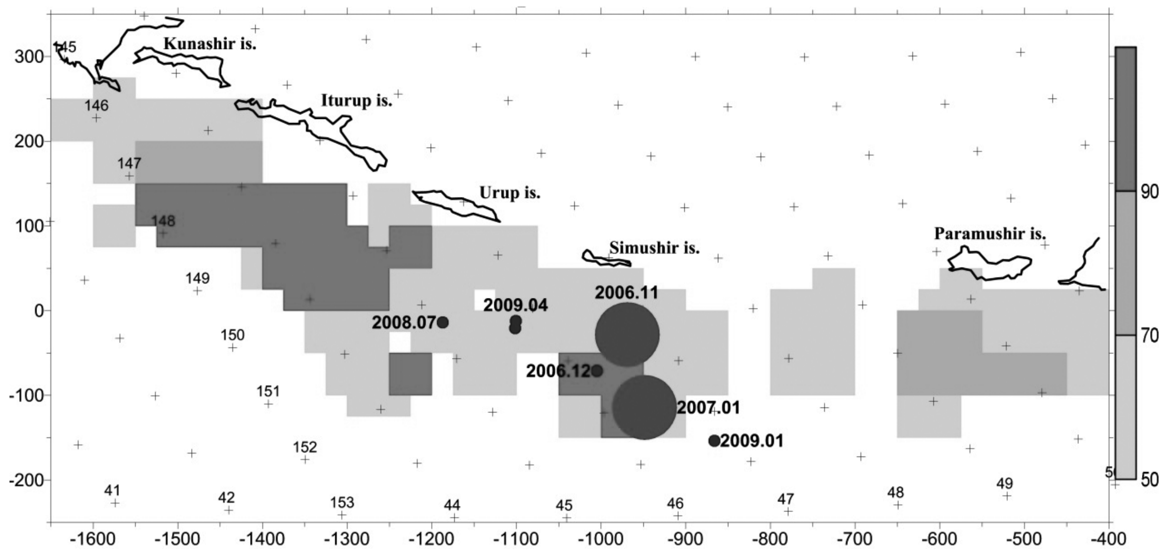


Figure 2. Map of expected earthquakes in the Kuril Islands for the period from 1 October 2006 to 30 September 2010. The map shows epicenters of earthquakes and their groups with $K_{\mathrm{pr}} \geq 13.5$ that occurred during the MEE validity period (4 years). The other symbols are the same as in Fig. 1. The axes of Cartesian coordinates are given in kilometers.

Table 2. Retrospective Prediction Results for the MEE Algorithm in New Zealand

Magnitude range	Conditional probability level, $P(D_1\|K)$		
	50 %	70 %	90 %
$M \geq 7.0$	5 (5)	4 (5)	**4 (5)**
$6.5 \leq M < 7.0$	4 (4)	4 (4)	**4 (4)**
$6.0 \leq M < 6.5$	10 (11)	10 (11)	**8 (11)**
$5.5 \leq M < 6.0$	16 (20)	16 (20)	**13 (20)**
Total	35 (40)	34 (40)	**29 (40)**
J_{MEE}	1.40	1.79	**2.76**

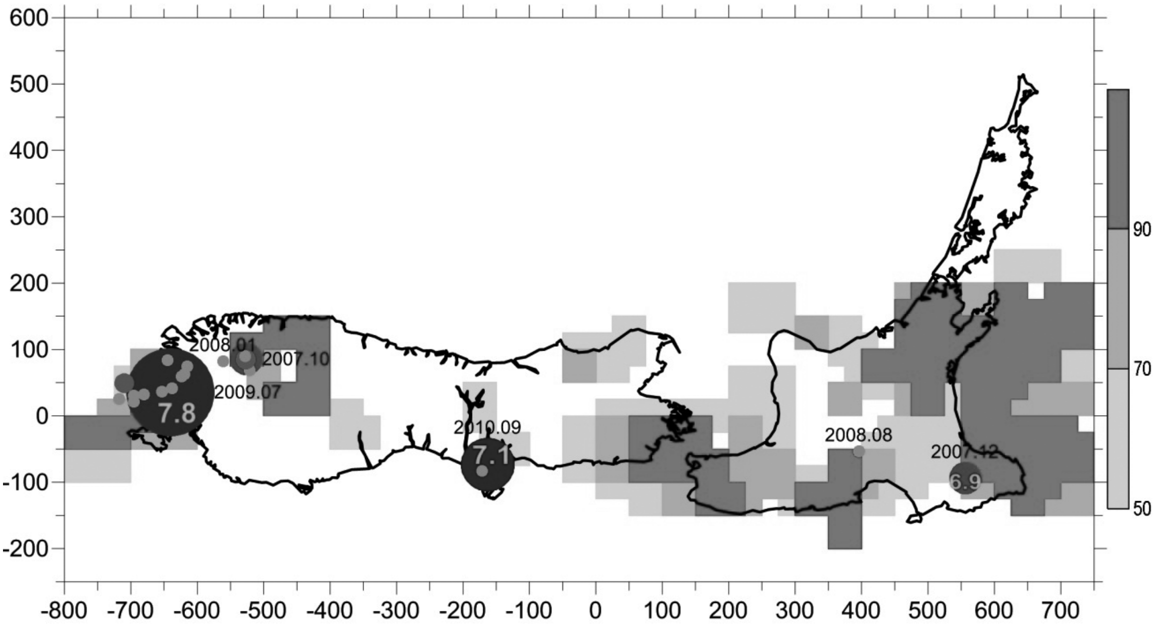


Figure 3. Map of expected earthquakes in New Zealand for the period from 1 January 2006 to 31 December 2010. The map shows epicenters of earthquakes and their groups with $M_{\mathrm{pr}} \geq 5.5$ that occurred during the MEE validity period (5 years). The dimensions of a square elementary cell are 50×50 km. The other symbols are the same as in Fig. 1. The axes of Cartesian coordinates are given in kilometers.

period from 1 January 2006 to 31 December 2010 (5 years). Table 2 contains retrospective prediction data for New Zealand for the whole series of maps of expected earthquakes.

Koyna–Warna reservoir site. Let us discuss in detail how maps of expected earthquakes for this region are compiled and results of their analysis.

2. Input Data and Selection of Parameters

The local earthquake catalogue for the Koyna–Warna area covering the period from 1996 to 2012 (approximately 17 years) and including 4,500 earthquakes with $M_{\mathrm{L}} = 0$–6.5 magnitudes that occurred in the depth range of $H = 0$–20 km was used as the database for this work. Linear dimensions of the seismic area under study are 40×60 km. Approximately half of all earthquakes included in the catalogue are the aftershocks of earthquakes with $M_{\mathrm{L}} \geq 4$. These aftershocks were not excluded from the catalogue when calculating time and space distributions of precursor parameters and expected earthquake map values. With $M_{\mathrm{c}} = 2.1$ selected as a representative magnitude, all subsequent calculations of seismic parameters used all earthquakes with $M_{\mathrm{L}} \geq 2.1$ magnitudes registered continuously starting from 1996 over the entire Koyna–Warna area. Average location errors were approximately 1 km for epicenters and 3 km for hypocenters.

A standard set of seismic predictor parameters (dynamic characteristics) used for expected earthquake mapping of seismically active regions with pronounced tectonic activity was used for the Koyna–Warna area: *b-value* of the magnitude-frequency relationship (so called Gutenberg-Richter law), number of earthquakes in the form of relative seismic quiescence *Nq*, number of earthquakes in the form of seismicity activation *Na*, released seismic energy in the form of energy quiescence *Eq*, released seismic energy in the form of energy activation *Ea*, and density of seismogenic ruptures K_{sf}. Each of these parameters and their mathematical definitions are described in detail in [2]. All dynamic predictor characteristics, excluding concentration of seismogenic ruptures K_{sf}, which has a cumulative nature and is a threshold value, were represented as time and space distributions of abnormal deviations from the respective long-term (background) levels scaled to the root-mean-square error of its definition (the so-called ξ-parameter). Time and space distributions of seismic parameters were calculated in half-overlapping rectangular grid cells $\Delta X \times \Delta Y$. As the base case scenario, we have selected the dimensions of a spatial cell equal to 10×10 km. When calculating parameter distributions of $K_{\rm sf}$, the basic cell dimensions were 5×5 km. The sliding time window value ΔT_T for calculation of current predictive characteristics was selected as $\Delta T_T = 3$ years with a shift $\Delta t = 3$ months.

Since there were no data on static predictor characteristics (that vary very little during the seismic cycle) for the Koyna–Warna area, they were not used for this paper. The MEE calculation methodology allows for such an approach.

In 1996–2012, 26 earthquakes and their groups with magnitudes $M_{\rm L} \geq 4.0$ occurred in the area under study (Table 3). Prediction of earthquakes in this magnitude range is of interest both from a social and economic point of view and a scientific point of view and their number is large enough to draw statistical conclusions. Among these earthquakes, four groups of events that include earthquakes with $5.0 \leq M_{\rm L} < 5.5$ were the largest. Seven groups include earthquakes with $4.5 \leq M_{\rm L} < 5.0$.

3. Calculation of Retrospective Statistical Characteristics for Seismic Regime Parameters

Retrospective statistical characteristics for precursor parameters were calculated for different alarm levels set by the researcher; after that, experts selected the values at which prediction reliability (i.e. the ratio of the average density of major earthquake flow during alarms (or in the alarm area) to their average density during the period of observations (or in the area of observations) for a specific precursor best matched the objective: either the largest number of predicted earthquakes over quite a long alarm time or the smaller number of predicted major earthquakes over a short alarm time (strategy by G.M. Molchan). The calculations were performed as described in [2]. Table 4 shows retrospective statistical characteristics for precursors with alarm levels selected by the expert for use in subsequent calculations. Note that reliability of most predictive characteristics J for the selected alarm levels proved to be more than 3, i.e. these characteristics can be regarded as *"quite useful"* (see Table 3.2 in [2]). For just one characteristic $\xi_{\rm ea}$, reliability was about half as much and equal to J =1.58, which is classified as "*useful*".

The results of using each characteristic to predict earthquakes with $M_{\rm L} \geq 4.0$ at the Koyna–Warna reservoir site are summarized in Table 3.

The analysis of the table suggests the following conclusions:

1. Only one group of earthquakes (# 12), which consisted of 3 events with the largest one having a magnitude of $M_{\rm L} = 5.0$, was preceded by abnormal, statistically significant values of all six predictive characteristics.
2. Of the total number of earthquakes, only 5 earthquakes (# 1, 2, 6, 22, and 25) were not preceded by any anomalies in any of the characteristics.
3. All four groups of earthquakes with the largest events with $M_{\rm L} \geq 5.0$ were preceded by anomalies in a number of characteristics.
4. Of all predictive characteristics, density of seismogenic ruptures $K_{\rm sf}$ is the most successful in terms of the number of predicted earthquakes. Using this characteristic, 88.5 % of earthquakes with $M_{\rm L} \geq 4.0$ were predicted.

Validity of a map of expected earthquakes obtained by averaging expectation times for all 6 characteristics ξ_b, ξ_{nq}, ξ_{na}, $\xi_{\rm eq}$, $\xi_{\rm ea}$, $K_{\rm sf}$, with the selected alarm levels, is $\Delta T_{\rm MEE} = 2.13 \pm 0.94$ years, whereas the expectation area for an earthquake with $M_L \geq 4.0$ is $\tilde{S}^k_{\rm exp} = 152 \pm 17$ km^2 (Table 4).

4. Calculation of Unconditional Probability of a Major Earthquake

To calculate the unconditional probability of a major earthquake in a spatial cell with the selected dimensions, data on major earthquakes (and their groups) that occurred in the area under study during the period of observations are used (Table 3). In this case, spatial cells must not be *overlapped* (they must be *independent*). Each seismic event (or a group of events) is represented by a certain nucleation area where typical changes in geophysical fields are observed, rather than by a single point corresponding to the hypocenter. The average major earthquake expectation area can be taken in a first approximation for a set of predictive characteristics as an estimated area of earthquake nucleation. Then the average number of major earthquakes and their groups that occur in the expectation area during the expectation time

Table 3. Retrospective prediction results for Earthquakes with $M_{\mathrm{L}} \geq 4.0$ that occurred in the Koyna–Warna Area from 1 January 1996 to 30 November 2012

No.	Date	Time	Geographic coordinates, grad.		Depth, km	Magni-tude	Prognostic feature					
			Lat.	Lon.	H	M_L	b	Nq	Na	Eq	Ea	K_{sf}
1	1996.04.26	12:19:32	17.17	73.71	7	4.4						
2	1997.04.25	16:22:53	17.35	73.76	3	4.4						
3	1998.02.11	01:08:47	17.17	73.77	6	4.3						+
	1998.02.14	00:59:49	17.15	73.73	10	4.2						+
4	1999.06.07	15:45:01	17.27	73.76	2	4.7			+			+
5	**2000.03.12**	**18:03:54**	**17.20**	**73.72**	**12**	**5.2**		+	+		+	+
6	2000.04.06	22:30:12	17.14	73.67	2	4.8						
7	**2000.09.05**	**00:32:43**	**17.20**	**73.77**	**14**	**5.3**		+				+
8	2000.12.08	13:23:05	17.11	73.74	7	4.1		+	+	+		+
9	2001.05.17	16:04:27	17.19	73.74	8	4.0			+		+	
10	2001.08.02	04:08:52	17.13	73.76	5	4.0		+	+	+		+
11	2003.03.27	06:18:23	17.34	73.79	8	4.1			+		+	
12	**2005.03.14**	**09:43:48**	**17.14**	**73.76**	**3**	**5.0**	+	+	+	+	+	+
	2005.03.15	**02:07:07**	**17.18**	**73.76**	**10**	**4.2**	+	+	+		+	+
	2005.03.26	**00:56:36**	**17.16**	**73.77**	**2**	**4.0**						
13	2005.06.07	21:32:06	17.24	73.72	14	4.2	+	+	+		+	+
14	2005.08.30	08:53:17	17.19	73.79	5	4.5						+
15	2005.11.20	18:50:41	17.20	73.76	5	4.0						+
16	2005.12.26	10:46:05	17.16	73.76	12	4.2						+
17	2006.04.17	16:39:59	17.16	73.77	8	4.6			+			+
18	2007.08.20	19:15:53	17.18	73.78	2	4.0			+		+	+
19	2007.11.24	10:57:48	17.14	73.79	9	4.3	+		+		+	+
20	2007.11.24	11:35:45	17.12	73.7	5	4.0		+			+	+
21	2008.07.29	19:10:51	17.31	73.74	4	4.2						+
22	2008.09.16	21:47:13	17.31	73.72	14	4.8						
23	2009.11.14	13:03:34	17.14	73.79	4	4.7	+	+	+		+	+
	2009.11.14	13:34:35	17.12	73.78	3	4.0						+
24	**2009.12.12**	**11:51:25**	**17.13**	**73.78**	**5**	**5.1**			+			+
	2009.12.12	**16:25:41**	**17.16**	**73.8**	**12**	**4.3**	+				+	+
25	2009.12.23	03:49:29	17.12	73.78	3	4.0						
26	2012.04.14	05:27:41	17.33	73.74	12	4.8		+		+		+
Total number of predicted earthquakes, N_{pr}							**6 (23)**	**10 (23)**	**14 (23)**	**4 (23)**	**11 (23)**	**23 (26)**
Total number of predicted earthquakes in %%							**26.1**	**43.5**	**60.9**	**17.4**	**47.8**	**88.5**
$M_{\mathrm{L}} \geq 5.0$							**2 (4)**	**3 (4)**	**3 (4)**	**1 (4)**	**3 (4)**	**4 (4)**
$4.5 \leq M_L < 5.0$							**1 (7)**	**2 (7)**	**2 (7)**	**1 (7)**	**1 (7)**	**4 (7)**
$4.0 \leq M_L < 4.5$							**2 (12)**	**4 (12)**	**7 (12)**	**2 (12)**	**6 (12)**	**11 (15)**

Note. The total number of earthquakes with the corresponding magnitudes is given in brackets.

Table 4. Retrospective statistical characteristics for predictive characteristics before earthquakes with $M_L \geq 4.0$ that occurred in the Koyna–Warna area from 1 January 1996 to 30 September 2012

Parameter K_i	Alarm level	Probability of detection $P(K_i\|D_1)$	Probability of false alarm $P(K_i\|D_2)$	Average expectation time, year $\tilde{T}_{\exp} \pm \sigma_t$	Average expectation square, km^2 $\tilde{S}_{\exp} \pm \sigma_t$	Real number of predicted earthquakes	Number of false alarm / Number of missed targets	Effectiveness of prediction in time J_t
ξ_b	+2.0σ	0.1190	0.0211	1.5±1.1	133±26	6	10/71	3.84
ξ_{nq}	-2.0σ	0.2024	0.0227	1.8±2.2	133±47	10	2/66	5.39
ξ_{na}	+2.0σ	0.3929	0.0100	2.6±2.5	164±40	14	0/45	4.78
ξ_{eq}	-1.2σ	0.1310	0.0358	1.9±1.7	175±61	4	3/71	3.41
ξ_{ea}	+1.5σ	0.2500	0.1431	3.8±3.0	145±42	11	13/59	1.58
K_{sf}	11.7	0.5684	0.1508	1.2±1.1	161±50	23	35/41	2.92

Note. Grid size: 10×10 km for ξ_b, ξ_{nq}, ξ_{na}, ξ_{eq}, ξ_{ea}, parameters and 5×5 km for K_{sf} parameter.

(period of MEE validity) will be equal to

$$\lambda = \frac{\tilde{S}^K_{\exp}}{S_{\text{obs}}} \cdot \frac{\Delta T_{\text{MEE}}}{T_{\text{obs}}} \cdot N_{\text{tot}},$$

where N_{tot} is the total number of major earthquakes and their groups; T_{obs} is the period of observations during which N_{tot} events occurred; S_{obs} is the area of observations where N_{tot} events occurred. We will call λ the major earthquake flow intensity.

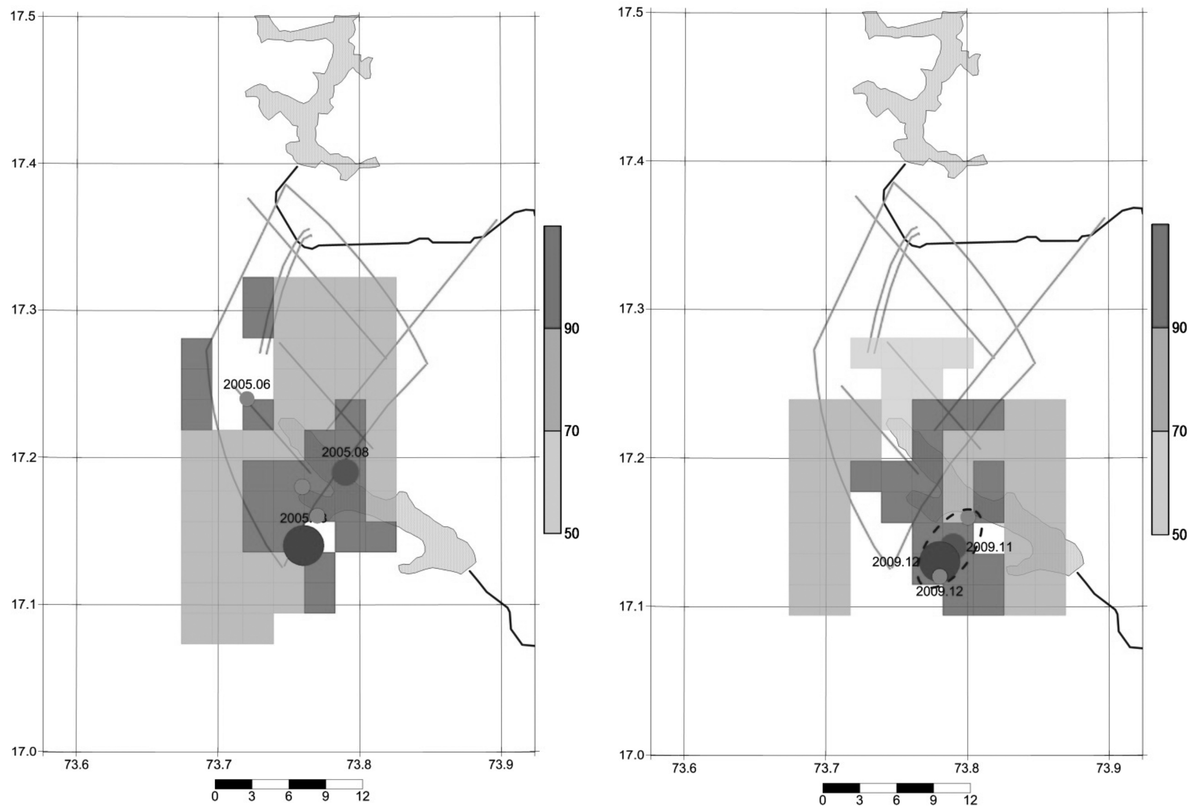
If we assume that the flow of major earthquakes obeys the Poisson distribution (and this is enough in a first approximation), then the unconditional probability of *one* major earthquake occurring in the expectation area during the expectation time will be equal to $P(D_1) = \lambda \exp(-\lambda)$ [1]. Therefore, $P(D_2) = 1 - P(D_1)$ is the probability of an earthquake not occurring. The resultant unconditional probability of a major earthquake $P(D_1)$ is assigned to each spatial grid cell. In our case, if we substitute the required parameter values, we obtain $P(D_1) = 0.1698$. Then $P(D_2) = 0.8302$. $P(D_1)$ values were assigned to each rectangular cell of the grid covering the area under study.

5. Calculation and Initial Analysis of Maps of Expected Earthquakes for the Koyna–Warna Area

All conditional probability values $P(D_1|K)$ for all spatial grid cells was called the Map of Expected Earthquakes for a period of time $[T_0 t_0 + \Delta T_{\text{MEE}}]$, where ΔT_{MEE} is the MEE validity. It is assumed that the occurrence of a major earthquake in this time interval is equally probable. However, it is appropriate to mention here the work by M.O. Kutsenko and A.D. Zavyalov [3] which shows that the occurrence of earthquakes in different one-year expectation time intervals is not equally probable. As it turned out, major earthquakes are most likely to occur during the first years after the precursor appears. The possibility of a major event was 25% during the first year and more than 70% during the first 5 years for almost all precursors. Please note that this work was based on data from tectonic earthquake catalogues from different seismically active regions of the world.

A series of 42 expected earthquake maps was developed for the Koyna–Warna area, from 1 July 2002 to 1 October 2012, with 3-month shift and 2-year prediction periods for each map. The period from 1 January 1996 to 30 June 2002 (6.5 years) was used to train the algorithm; therefore, the earthquakes that occurred during this period were not included in the assessment of retrospective prediction results and MEE algorithm effectiveness.

All earthquakes with $M_L \geq 4.0$ that occurred during the prediction period of the map were plotted on each map of expected earthquakes; then the area of alarm zones with different conditional probability levels P $(D_1|K)$ was calculated. Fig. 4a shows a typical map of expected earthquakes for the Koyna–Warna area for the two-year period from 1 October 2003 to 30 September 2005. Another MEE with a different prediction period is shown in Fig. 4b. As can be seen on both maps, major earthquakes



a) b)

Figure 4. Map of expected earthquakes for the period from 1 October 2003 to 30 September 2005 (a) and from 1 January 2009 to 31 December 2010 (b). The map shows epicenters of earthquakes and their groups with $M_L \geq 4.0$ that occurred during the MEE validity period (2 years). The size of circles is proportional to the length of rupture in the earthquake focus on the map scale. The dashed ellipse indicates a group of earthquakes that occurred on 14-26 March 2005 (a) and 12–23 December 2009 (b). The dimensions of a square elementary cell are 5×5 km. The axes show the geographical coordinates in degrees.

occurred in the zones with the conditional probability level $P(D_1|K) \geq 90$ % during the prediction period.

The results of the analysis of the whole MEE series are summarized in Table 5. As can be seen from the table, during the retrospective prediction period from 1 January 2003 to 30 September 2012 at the conditional probability level $P(D_1|K) \geq 90$ %, which is more than 5 times higher than the level of unconditional probability, both largest earthquakes with $M_L \geq 5.0$ (# 12 and 24), 3 earthquakes out of 5 in the $4.5 \leq M_L < 5.0$ range (No. 14, 23, and 26), and 5 out of 9 earthquakes with $4.0 \leq M_L < 4.5$ (# 13, 15, 19, and 25) were predicted. Out of 16 major earthquakes, a total of 9 earthquakes (56.3 %) occurred in the zone with $P(D_1|K) \geq 90$ %. In this case, the area of observations S_{obs} with the seismic activity level of 0.1 events per year falling within the zone with the conditional probability level of 90 % was 20.4±8.4 %. The integral prediction effectiveness of the MEE algorithm at this level of conditional probability was 2.76. Table 5 also shows similar data for other levels of conditional probability (50 % and 70 %).

The prediction can be verified in real time using the most recent map in the series with the prediction period from 1 October 2012 to 30 September 2014 (Fig. 5) which was calculated in advance. As can be seen from Fig. 5, two areas are the most hazardous: one of them is located to the south of the Koyna Dam and the other, which is larger, is located to the north of the Warna Dam. During the prediction period only one earthquake with $M_L \geq 4.0$ took place in the area under study. It was occurred

Table 5. Retrospective prediction results for earthquakes with $M_L \geq 4.0$ that occurred in the Koyna–Warna area from 1 July 2002 to 30 November 2012, using MEE algorithm.

Magnitude range	Conditional probability level, $P(D_1\|K)$		
	50 %	70 %	90 %
$M_L \geq 5.0$	2/2	2/2	**2/2**
$4.5 \leq M_L < 5.0$	4/5	3/5	**3/5**
$5.0 \leq M_L < 4.5$	7/9	6/9	**4/9**
Total number of predicted earthquakes, N_{pr}	13	11	**9**
Number of predicted earthquakes in %%	81.3	68.8	**56.3**
Total number of strong earthquakes that occurred in the area, N_{tot}	16		
Average alarm square $\tilde{S}_{al}/S_{obs}$ in % %	40.5±7.6	36.6±8.8	**20.4±8.4**
MEE effectiveness J_{MEE}	2.01	1.88	**2.76**

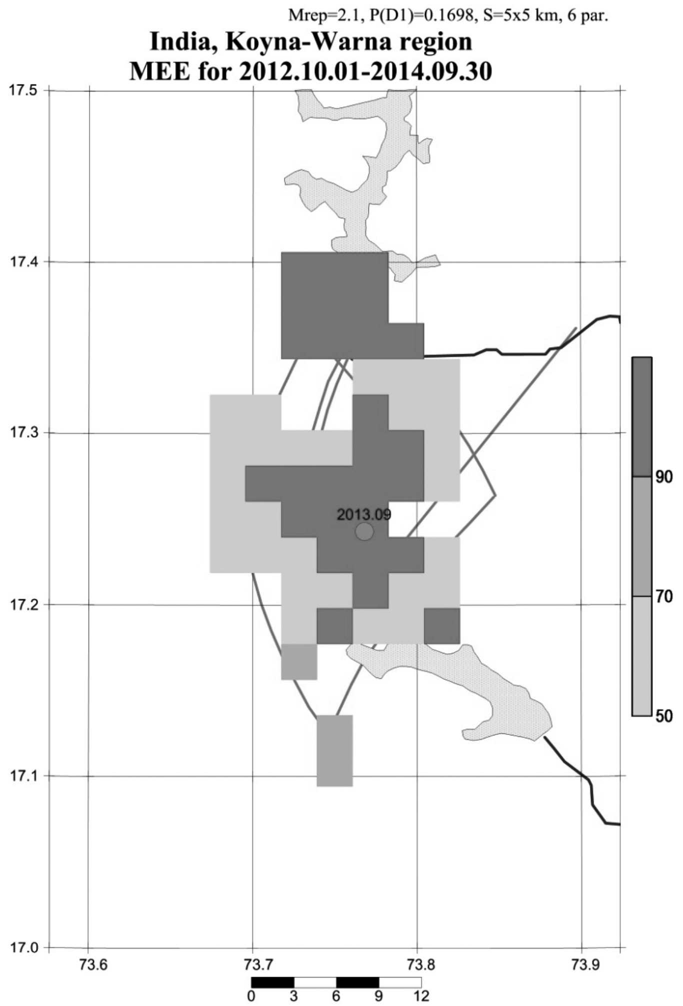


Figure 5. Map of expected earthquakes for the Koyna–Warna reservoir site (India) for the period from 1 October 2012 to 30 September 2014 (real-time prediction target). The dimensions of a square elementary cell are 5×5 km. The axes show the geographical coordinates in degrees.

almost in the center of large south zone with conditional probability $P(D_1|K) \geq 90$ %.

Conclusions

The paper contains examples of MEE for a variety of seismically active regions all over the world and retrospective prediction results for each of them.

The paper also provides a detailed description of MEE calculations for the Koyna–Warna area and initial analysis of the results. A retrospective analysis of prediction effectiveness has been made for each of the seismic precursors used in the MEE algorithm. It transpired that the density of seismogenic ruptures is the most successful characteristic of all predictive characteristics in terms of the number of predicted earthquakes. The resultant unconditional probability of a major earthquake in grid cells is $P(D_1) = 0.1698$.

The findings of using the MEE algorithm in a classical area with a transient seismic regime for the first time were very encouraging. They showed that its prediction effectiveness equal to 2.76 was quite high. Zones with conditional probability levels $P(D_1|K) \geq 90$ % experienced 56.3 % of all earthquakes with $M_L \geq 4.0$. The alarm area was 420.4 ± 8.4 % of the total area of observations. The MEE algorithm was particularly efficient in predicting the largest earthquakes in the Koyna–Warna area that occurred during the retrospective prediction period. At a later stage, more accurate adjustment of algorithm parameters may improve the overall prediction effectiveness. Integral predictive effectiveness estimates obtained when the MEE algorithm was used for the Koyna–Warna reservoir site are close to the average values of these parameters for all previous seismically active regions. These findings may be considered proof of the flexibility of the proposed algorithm.

The prediction was verified in real time using the map of expected earthquakes for the period from 1 October 2012 to 30 September 2014. The only one earthquake with $M_L \geq 4.0$ took place in the center of zone with conditional probability $P(D_1|K) \geq 90$ %.

References

1. Ventsel E.S. *Probability Theory.* Moscow, Nauka Publ., 1969, 576 p. (In Russian)
2. Zavyalov A.D. *Medium-Term Earthquake Prediction: Fundamentals, Methodology, Implementation.* Moscow, Nauka Publ., 2006, 254 p. (In Russian)
3. Kutsenko M.O., Zavyalov A.D. Probability of an Earthquake in the Expectation Time Interval Based on a Set of Predictive Characteristics. In *Proc. of the 12th Urals Youth Scientific School for Geophysics. Perm, 21–25 March 2011*, p. 131–136. (In Russian)

Received 8 April 2016