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CONSTRUCŢII. ARHITECTURĂ

PROBABILISTIC MODELLING OF THE SEISMIC HAZARD USING THE ROMANIAN EARTHQUAQE CATALOGUE

BY

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The actual trend of performance based modelling of the seismic action is to adopt probabilistic models of the seismic hazard. In the first part of the paper are presented theoretical aspects of the seismic hazard definition from the probabilistic point of view as "a function $P(Y > y)$ that describes the probability that in a given region (M) and for a time interval (T), the value of a parameter, Y (for example: macroseismic intensity, acceleration, velocity and displacement of the soil) to overpass the given value (y) as an effect of a seismic event" [4]. The probabilistic study of the seismic hazard gives the possibility to implement new parameters, such as: the likeliness and the occurrence frequency of the seismic events. Nowadays most of the international standards adopted the probabilistic analysis of the seismic hazard as a complementarity of the deterministic analysis. In the second part of the paper are presented the results of the probabilistic analysis for Vrancea region using the Gumbel I probabilistic model that has the parameters determined throughout the extreme values statistical method.

1. Introduction

The seismic events are extremely complex phenomena, from the point of view of randomness and unpredictability representing important causes for the most violent and frequent damages or even the collapse of the structures.

The traditional methods to determine the maximum deterministic response from the seismic analysis of structures is improved today by determining the probabilistic approaches for the modelling of the seismic events. The majority of international seismic standards have adopted the probabilistic modelling as a complementary analysis of the seismic hazard. In this way the structural engineer has the possibility to add up in the deterministic analysis some probability parameters, such as: medium period of occurrence or the occurrence probability of a seismic event.

The Romanian technical regulation MP-026-04* [4] describes different models and methods to determine the seismic hazard from a probabilistic point of view, according to the parameters estimated for Vrancea region.

EUROCODE 8 [1] provides a definition of the seismic actions based on the seismic hazard. The seismic hazard level is defined by the peak ground motion acceleration determined for a mean period of recurrence of seismic events.

American pre-standard FEMA 356 [2], [3] presents probabilistic models of the seismic actions depending on two factors: the level of the seismic hazard of the site and the spectral acceleration response. The design seismic force is represented by the Critical Earthquake defined by the maximum value of the ground acceleration for a probability of exceedance in a 50-year period.

2. Models of Seismic Events Based on Seismic Hazard

In the Romanian technical regulation MP-026-04* [4] some statistical models are described to identify the seismic hazard. These models are: the Eipstein and Lomnitz (Gumbel I) model, the extreme values (Gumbel III) model and Der Kiureghian and Ang model.

The statistical methods used to estimate the necessary parameters in the probabilistic analysis of the seismic hazard are briefly described in the Romanian technical regulation MP-026-04* [4]. These methods are: the extreme value method, the Bayesian method, the optimization method, the composition method, the zonation method and the simulation method.

In literature [4] the seismic hazard, H, is defined as a function, $P(Y > y)$, describing the probability that in a given place (M) and in a certain time interval (T), the value of the parameter, Y (macro-seismic intensity, ground acceleration, velocity or displacement), can overpass the given value (y) as an effect of a seismic event. Analytically expressed, the seismic hazard is defined as

$$H = P(Y > y). \tag{1}$$

The probabilistic assessment of the seismic hazard is based on Cornell-McGuire methodology [1], [4], which takes into account:

a) The identification of the independent sources of seismic activity and determination of the Gutenberg-Richter relationship from contribution of each source

$$\log N = a - bM, \tag{2}$$

where: N is the number of earthquakes, of equal or bigger magnitude than M, expected to occur in a certain time interval; a – the logarithm of the earthquakes number of magnitude $M \geq 0$, that can occur in the same time interval; b – the curve slope characterizing the ratio between strong and weak earthquakes.

b) The fitting of the attenuation relationship on peak ground motion parameter. The attenuation law of the ground motion parameters in respect to the distance to the earthquakes focus is the smooth curve fitted to the data by a non-linear regression or multi-regression procedure.

c) The calculation and mapping of the peak ground motion parameter having a specified probability of non-exceedance at the site during structure life:

c_1) peak ground acceleration, velocity and displacement (PGA, PGV, PGD);

c_2) effective peak acceleration (EPA) and effective peak velocity (EPV);

c_3) elastic spectral acceleration (SA) and spectral velocity (SV) for a damping ratio of 0.05.

The occurrence probability of an earthquake is equivalent with the probability of exceedance of the seismic event for a given period and can be defined as

$$T_R = \frac{T}{\ln\left[1 - P(Z > z)\right]}. \tag{3}$$

where: T is the time interval (for the analysis: life-time of a structure); $P(Z > z)$ – the probability of exceedance of the seismic event in the time interval T.

d) The construction of uniform hazard site dependent spectra for design.

The EUROCODE 8 [1] also defines the seismic hazard using the Probabilistic Seismic Hazard Analysis (PSHA) based on the Cornell-McGuire methodology [1], [4].

The American pre-standard FEMA 356 [2], [3] defines the earthquake demands in function of location of the building with respect to the earthquake focus, geological characteristics and ground motion hazard levels. In this pre-standard the hazard levels are defined using a probability of exceedance for a 50-year period, as presented in Table 1.

Table 1
Hazard Levels and their Corresponding Mean Periods

Earthquake having probability of exceedance	Mean return period years
50%/50 years	72
20%/50 years	225
10%/50 years	474
2%/50 years	2,475

In order to satisfy the basic safety objectives the code uses for seismic design two main levels of earthquake hazards:

a) the Basic Safety Earthquake 1 (BSE-1), defined as that ground shaking having a 10% probability of exceedance in 50 years;

b) the Basic Safety Earthquake 2 (BSE-2) or the Maximum Considered Earthquake (MCE), defined as that ground shaking having a 2% probability of exceedance in 50 years.

3. Study Case for Modelling Seismic Hazard

The study case illustrates the procedure of determining the occurrence of the biggest earthquake for a certain interval of time in the Vrancea region, based on *a priori* seismic events data. In order to perform the probabilistic analysis the Gumbel I statistical model [4] has been used.

The statistical method used for construction of the Gumbel I model is the extreme value one [9]. This method deals with extreme values of some statistic variable which, in the case of earthquakes, can be the magnitude or the maximum ground acceleration. The chosen statistic variable in this study case is the maximum earthquake moment magnitude corresponding to the real data of seismic events happened in the time interval 1934...2005. The approach has the advantage that the extreme values of a certain geophysical variable are better known, more homogeneous in time and more accurately determined, doesn't need a detailed knowledge of the base distribution and is easy to use and understand. Disadvantages using this approach are that the influence of the climate changes or the seismic fluctuations on the geophysical variables, and the extrapolation of the relations for data outside the known domain can not be included.

The present study case uses data retrieved from the National Institute of Research and Development for Earth Physics, Romania [10], in the form of a seismic catalogue for the period 1934-2005 presented in the Table 2.

Table 2
Earthquake Moment Magnitude Catalogue for the Vrancea Region in the Time Interval 1934-2005

Date	Origin-Time	Depth	M_w	NS/ NA/ NM	RMS/ SD	Q	REG
1934/03/29	20:06:51.0	90.	6.6	/ /	/	C	$S=1$
1935/09/05	06:00:00.0	130.	6.0	/ /	/	D	$S=1$
1936/05/17	17:38:02.0	140.	6.0	/ /	/	D	$S=1$
1937/01/26	14:34:00.0	100.	5.4	/ /	/	D	$S=1$
1938/07/13	20:15:17.0	120.	6.0	/ /	/	C	$S=1$
1939/09/05	06:02:00.0	120.	6.2	/ /	/	C	$S=1$
1940/11/10	01:39:07.0	150.	7.7	/ /	/	C	$S=1$
1941/01/29	07:04:00.0	130.	5.5	/ /	/	D	$S=1$
1942/04/13	03:07:22.0	70.	5.6	/ /	/	D	$S=1$
1943/04/28	19:46:50.0	100.	5.9	/ /	/	C	$S=1$
1944/02/25	16:59:00.0	100.	5.6	/ /	/	D	$S=1$
1945/09/07	15:48:26.0	80.	6.8	/ /	/	C	$S=1$
1946/11/03	18:47:01.0	140.	6.0	/ /	/	C	$S=1$
1947/10/17	13:25:20.0	130.	5.8	/ /	/	D	$S=1$
1948/05/29	04:48:55.0	130.	6.3	/ /	/	C	$S=1$
1949/12/26	03:36:10.0	135.	5.7	/ /	/	C	$S=1$
1950/06/20	01:18:54.0	160.	5.9	/ /	/	C	$S=1$
1951/03/18	11:32:30.0	150.	5.3	/ /	/	D	$S=1$
1952/08/03	16:36:14.0	150.	5.5	/ /	/	D	$S=1$
1953/05/17	02:33:54.0	140.	5.4	/ /	/	C	$S=1$
1954/10/01	13:30:00.0	60.	5.6	/ /	/	D	$S=1$
1955/05/01	21:22:52.0	135.	5.8	/ /	/	C	$S=1$
1956/05/07	03:54:12.0	100.	5.0	/ /	/	C	$S=1$
1957/12/02	04:21:57.0	140.	4.7	/ /	/	D	
1958/06/25	07:22:12.0	150.	5.0	/ /	/	C	
1959/08/19	15:32:03.0	150.	5.5	/ /	/	D	
1960/10/13	02:21:25.0	160.	5.9	/ /	/	C	
1961/11/18	03:18:44.2	100.	5.1	/ /	/	D	$S=1$
1962/08/30	07:46:27.1	108.	5.3	/ 13/	/	D	$S=1$
1963/01/14	18:33:24.2	117.	5.8	/ 48/	/	C	$S=1$
1964/06/17	13:38:15.9	145.	4.8	/ 7/	/	C	$S=1$
1965/01/10	02:52:23.9	128.	5.8	/ 34/	/	C	$S=1$
1966/10/02	11:21:44.8	140.	5.9	/ 95/	/	C	$S=1$
1967/02/27	21:00:42.0	42.	5.0	/ /	/	C	$S=1$
1968/01/06	10:23:49.1	163.	5.0	/ 33/	/	C	$S=1$

Table 2

Continuation

Date	Origin-Time	Depth	M_w	NS/ NA/ NM	RMS/ SD	Q	REG
1969/04/12	20:38:39.6	8.	5.2	/ /	/	B	$S=1$
1970/07/10	14:18:58.8	33.	4.7	/ 19/	/1.1	C	$S=1$
1971/07/18	16:18:22.8	137.	3.8	/ 42/	/1.1	C	$S=1$
1972/08/23	18:00:31.3	82.	4.0	/ 46/	/1.3	C	$S=1$
1973/08/20	15:18:28.3	73.	6.0	/ 49/	/1.0	C	$S=1$
1974/04/17	01:31:33.9	33.	4.9	/ 18/	/1.2	D	$S=1$
1975/12/27	18:32:21.2	129.	5.3	/ 42/	/	C	$S=1$
1976/10/01	17:50:43.2	146.	6.0	/ 29/	/1.3	C	$S=1$
1977/03/04	19:21:54.1	94.	7.4	/ /	/	B	$S=7$
1978/10/02	20:28:52.6	164.3	5.2	/ 45/	/1.1	B	$S=1$
1979/05/31	07:20:06.3	120.	5.3	/ 79/	/1.0	B	$S=1$
1980/01/14	15:07:54.5	141.	5.1	/ 81/	/1.4	B	$S=1$
1981/07/18	00:02:58.6	166.1	5.5	/ 10/	/ .3	B	$S=1$
1982/12/01	16:52:56.4	145.1	4.3	/ 8/	/0.4	C	$S=1$
1983/01/25	07:34:50.0	149.8	5.6	/ 9/	/0.7	C	$S=1$
1984/02/12	19:09:00.4	124.0	4.7	/ 10/	/0.6	C	$S=1$
1985/08/01	14:35:04.3	93.5	5.8	/ 21/	/0.4	B	$S=1$
1986/08/30	21:28:37.0	131.4	7.1	15/ 16/	/	A	$S=8$
1987/09/04	01:40:29.9	160.2	5.0	/ 18/	/0.2	B	$S=1$
1988/01/07	10:21:44.5	139.2	4.6	/ 10/	/0.1	C	$S=1$
1989/05/21	02:15:41.9	133.4	4.4	6/ 10/ 6	.19/	A	$S=2$
1990/05/30	10:40:06.4	90.9	6.9	12/ 14/	.20/	A	$S=2$
1991/07/12	10:42:21.4	11.0	5.6	/ /	/	A	$S=5$
1992/03/31	15:04:38.2	153.6	4.7	9/ 16/ 7	.24/	A	$S=3$
1993/07/30	14:25:54.3	123.0	4.4	8/ 16/ 5	.22/	A	$S=3$
1994/06/06	07:28:45.3	135.7	4.3	7/ 6/ 6	.01/	C	$S=3$
1995/09/06	10:58:45.9	119.7	4.1	8/ 15/ 8	.16/	A	$S=3$
1996/06/07	05:09:23.1	126.2	4.6	12/ 17/ 5	.28/	A	$S=4$
1997/11/18	11:23:16.3	123.0	4.7	24/ 45/ 20	.52/	D	$S=4$
1998/03/13	13:14:38.8	154.8	4.7	24/ 47/ 23	.39/	A	$S=4$
1999/04/28	08:47:56.0	151.1	5.3	25/ 49/ 25	.39/	A	$S=4$
2000/04/06	00:10:38.8	143.4	5.0	17/ 34/ 17	.45/	D	$S=4$
2001/05/24	17:34:02.5	143.7	4.9	22/ 21/ 6	.27/	A	$S=3$
2002/11/30	08:15:48.7	166.4	4.7	10/ 16/ 6	.15/	A	$S=3$
2003/10/05	21:38:18.0	145.6	4.6	8/ 13/ 5	.22/	A	$S=3$
2004/10/27	20:34:36.4	98.6	6.0	16/ 17/ 3	.21/	A	$S=3$
2005/14/05	03:53:21	147	5.2				

Legend of Sources:

$S=1$ Constantinescu L., Mârza V., 1980 catalogue updated to July 1988.

$S=2$ Romplus catalogue: RoNet analog seismograms, Hypo/Hypoplus program.

$S=3$ Romplus catalogue: RoNet digital data, Hypo/Hypoplus program.

$S=4$ Romplus catalogue: RoNet and K2 digital data, Hypoplus program.

$S=5$ Radu C., open-file report.

$S=6$ Oncescu M.C., Bonjer K., Tectonophysics, *272*, 291-302 (1997).

$S=7$ NEIS/ISC catalogue, Mw by Oncescu M.C., Bonjer K., Tectonophysics, *272*, 291-302 (1997).

$S=8$ Trifu C.I., Oncescu M.C., Ann. Geophys., **5B**, 727-730, Mw by Oncescu M.C., Bonjer K., Tectonophysics, *272*, 291-302 (1997).

The equation (2) becomes

$$\ln N_M = \ln \alpha - \beta M, \tag{4}$$

defining the expected annual number of earthquakes with a magnitude bigger than M, where α and β are parameters recommended by different authors, for different periods of times and are presented in Table 2.

Using the statistical method based on extreme values [4], [9] the equation (4) became of form

$$\ln N_M = 22.89 - 4M. \tag{5}$$

The medium period of recurrence, T_M, of a seismic event with a magnitude grater than M is computed from the relationship

$$\ln T_M = 4M - 22.89. \tag{6}$$

Than, the occurrence probability, $H_T(M)$, of an earthquake with magnitude M or bigger in a period of time T, is given using the relation

$$H_T(M) = 1 - \exp(-\alpha T e^{-\beta M}). \tag{7}$$

The obtained results based on the above described computational approach illustrated before are presented in Fig. 1 as a comparison between percentile values of the occurrence probabilities for different moment magnitudes at specific time periods.

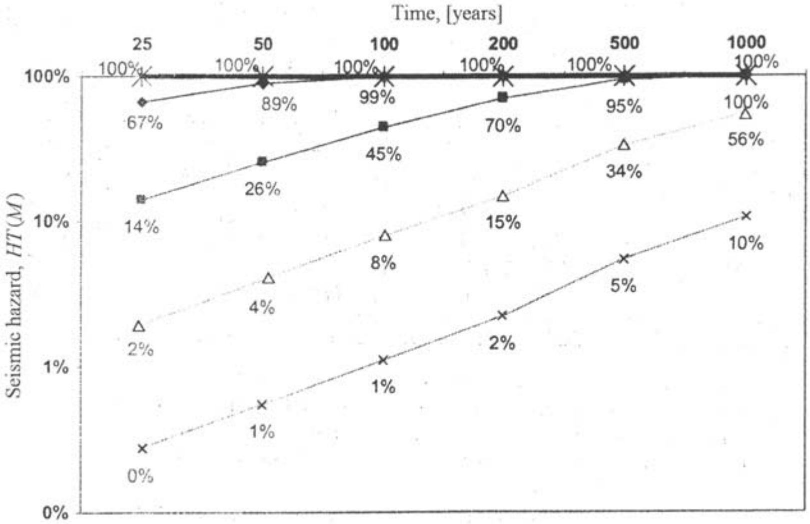

Fig. 1.- Seismic hazards for different values of moment magnitudes registered in Vrancea region with respect to certain occurrence periods of time; moment magnitudes: —✳— $M = 6$; —◆— $M = 6.5$; —■— $M = 7$; —△— $M = 7.5$; —×— $M = 8$.

The representation of the obtained results leads to the identification of probabilities for occurrence of major seismic events having moment magnitudes between 6 and 6.5.

Thus, for a seismic event with a moment magnitude of 6 the occurrence probability is 100% for a recurrence period of 25 to 1,000 years.

A seismic event with the moment magnitude 6.5 has the occurrence probability of 67% for a recurrence period of 25 years, 89% for a recurrence period of 50 years, 99% for a recurrence period of 100 years and 100% for a recurrence period of 200 to 1,000 years.

In comparison with the important seismic event that had the moment magnitude of 7.4 and occurred in 1977 in Romania, the graph from Fig. 1 shows that the occurrence probabilities for such a seismic event are of 2% for a period of time of 25 years, 4% in 50 years, 8% in 100 years, 15% in 200 years, 34% in 500 years and 56% in 1,000 years.

4. Conclusions

Some theoretical aspects regarding the probabilistic aspects of today seismic design based on the seismic hazard using the probabilistic approach are presented.

This probabilistic approach permits the embedding of the uncertainties and earthquake's occurrence frequencies for given periods of years.

The seismic hazard is expressed using an exceeding probability, so it can be compared with others types of seismic hazard. Thus, for medium periods of recurrence it can be identified the probability for earthquake occurrence of a certain magnitude.

The disadvantages are that the probabilistic analysis depends on the accuracy of input data and on the methods used to determine the seismic hazard.

Finally, a methodology to determine the recurrence of a seismic event was pointed out using the probabilistic approach based on the statistical extreme value method.

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MODELAREA PROBABILISTĂ A HAZARDULUI SEISMIC UTILIZÂND CATALOGUL ROMÂNESC DE CUTREMURE

(Rezumat)

Tendinţa actuală în modelarea acţiunii seismice în cadrul conceptului de analiză seismică, bazat pe performanţă, este cea de adoptare a modelelor probabiliste privind hazardul seismic. In prima parte a lucrării se prezintă aspecte teoretice de definiţie a hazardului seismic din punct de vedere probabilist ca „o funcţie $P(Y > y)$ ce descrie probabilitatea ca într-un loc dat (M) şi într-un anumit interval de timp (T), valoarea unui parametru Y (ca de exemplu: intensitatea macroseismică, acceleraţia, viteza sau deplasarea solului) să depăşească valoarea dată (y) ca efect al producerii unui cutremur" [4]. Studiul probabilist al hazardului seismic permite implementarea unor parametri, precum incertitudinea şi frecvenţa apariţiei evenimentelor seismice. Actualmente majoritatea standardelor internaţionale au adoptat analiza probabilistică a hazardului seismic ca o complementaritate a analizei deterministe. Partea a doua a lucrării prezintă rezultatele analizei probabiliste a hazardului seismic din regiunea Vrancea utilizând modelul probabilist Gumbel I cu parametri determinaţi prin metoda statistică a valorilor extreme.