Seismic hazard mapping using R-CRISIS

E Cutia¹, V Țurcan¹,
¹Technical University of Moldova, Faculty of Construction, Geodesy and Cadaster, Republic of Moldova.

E-mail: evgheni.cutia@cms.utm.md

Abstract. This article presents methods and software used to develop a seismic hazard map. As an example, the territory of the Republic of Moldova is being studied, which is affected by subcrustal earthquakes of medium depth in the Vrancea seismic area. The elaboration of the map is based on the theoretical model of probabilistic seismic hazard assessment established and described in detail in the specialized literature. In order to facilitate and minimize errors, specialized software was used, one of this software is R-CRISIS, a software created and presented for premier in 1986 by Professor Mario Ordaz at the Institute of Engineering UNAM, Mexico and which is continuously being developed and improved. R-CRISIS allows the users to perform a big range of deterministic and probabilistic analyses through a user-friendly interface.

1. Introduction
Natural hazards represent a real challenge not only for engineers, but for entire society as well. In order to manage and have a good emergency management policy in case of natural catastrophe, every country relies on different kinds of documents, statistics and maps. In this paper is presented how a seismic hazard map could be developed using specialized software. A hazard map represents graphical delimitation of affected or vulnerable areas to a particular phenomenon. As for seismic hazard map, the definition remains unchanged, only the phenomena are known – earthquake; so, one can state that a seismic hazard map is a graphical representation of a particular territory that is divided in small areas where the ground shaking, caused by earthquake, have the same behaviour and characteristics. Ground shaking is defined in terms of some parameter, usually peak ground acceleration (PGA), spectral acceleration or macroseismic intensity (e.g., EMS-98) [1].

1.1. Uses of seismic hazard maps
Generally speaking, hazard maps could be divided into two groups: maps for regulatory purposes and maps for information purposes.

![Figure 1. Applicability of seismic hazard map [2]](image-url)
1.2. Seismic hazard evaluation
In present there are two methods of seismic hazard assessment: probabilistic seismic hazard assessment (PSHA) and deterministic seismic hazard assessment (DSHA). DSHA is a method for estimating location-specific seismic hazard that is affected by the maximum earthquake from the controlling sources that can influence the specific location. Probabilistic seismic hazard is detailed described in [3,4,5,6,7]. PSHA for a site is developed considering all ground motions that can occur in the specified seismic zones of any possible magnitude and/or any possible distance between source and site. The main advantage of PSHA is that it combines all of accidental uncertainties that comes from the analysis of seismic zone parameters from a future earthquake at particular site [6]. PSHA provides a probabilistic approach of a characteristic unit such as ground acceleration.

One should understand that the mapping process is the last step in hazard assessment. In order to get to this final level, we need to perform a seismic hazard assessment.

2. Software R-CRISIS
R-CRISIS is a software that works on Windows Operating System and has capability to carry out probabilistic seismic hazard analysis using a fully probabilistic approach [8]. The first version of software was issued in 1986 by Professor Mario Ordaz - the lead author and was software with a command line interface developed in FORTRAN [8]. In 2007 the program was upgraded and now provides a user-friendly environment to perform seismic hazard assessment. R-CRISIS software is logically organized in six main tabs: File, Input, GMPE Analyzer, Run, Hazard and Tools.

The work in this software can be described in few steps as follows:

- **Adding Map Data** – at this step user should have a reference map in *.shp shapefile format of region that is analysed. It should be pointed out that R-CRISIS uses the World Geodetic System 84 (WGS-84) projection system and does not make any changes of coordinate projection. In addition to the map, the program offers user to add a text file with cities that could be subjected to hazard assessment (see Figure 2).

- **Computation Site Data** – is used to define a site where the PSHA is computed. Computation can be performed for a grid with a given step or for a specific site and output is required in terms of hazard curves (see Figure 3).

- **Source Geometry Data** – intend of this panel is to provide a fast and easy way of inserting the geometry of seismic sources. Various geometric models are realized in R-CRISIS software that characterize seismic sources. In this article will be used area-plane sources that are inserted as a set of vertexes which create a plan. Line, point and grid sources are available also (see Figure 3).

- **Spectral Ordinates Data** – in this window user can define number of spectral ordinates and their fundamental periods (see Table 1)

- **Seismicity Data** – for each seismic source defined in **Source Geometry Data**, user should specify seismicity parameters. R-CRISIS, by default, assigns modified G-R seismicity model to each source (see Table 2).

- **Attenuation Data** – in R-CRISIS, ground motion prediction model could be added from a predefined list of existing attenuation laws or could be used a custom *.atn file, created by user.

2.1. Adding Map Data
For map data, authors had prepared 2 types of file to add in software:

- A shapefile (*.shp) of Republic of Moldova in WGS-84 system of coordinates;
- A text file (*.txt) with 5 biggest cities as follows (Name of state, name of city, longitude, latitude):
  - Chisinau District, Chisinau City, lat $47^\circ0'59''$ and long $E 28^\circ52'0''$.
  - Balti District, Balti City, lat $47^\circ45'41''$ and long $E 27^\circ55'44''$.
  - Cahul District, Cahul City, lat $45^\circ54'18''$ and long $E 28^\circ11'47''$.
  - Stefan-Voda District, Stefan-Voda City, lat $46^\circ30'55''$ and long $E 29^\circ39'47''$.
  - Edinet District, Edinet City, lat $87^\circ10'14''$ and long $E 27^\circ18'15''$. 
2.2. Computation Site Data
In site data computation dialog window was chosen the Grind of sites option for performing PSHA. Was defined origin of the grid and incremented with the number of needed lines to cover all territory in two orthogonal directions. As the base point was chosen coordinates at latitude \( N 45°20′24″ \) and the longitude \( E 26°29′23″ \). The grind size was chosen to be equal of 40 vertical and 36 horizontal lines with the increment of 0.1° or 11.1 (\( km \)). The resultant map with grid point is presented in Figure 2.

2.3. Spectral Ordinates Data
This screen allows entering the parameters for each spectral ordinate (or, in general, intensity measure) for which seismic hazard will be computed. The values of spectral ordinates for defining fundamental periods for each spectral ordinate are entered. The measure unit is \( gal \) or \( cm/s^2 \). In this case study spectral ordinates are assigned for time periods of 0.01 sec (i.e., PGA), 0.2 sec and 0.4 sec.
Table 1. Spectral ordinates.

| Period index | T (s) | Lower limit | Upper limit | Units |
|--------------|-------|-------------|-------------|-------|
| 1            | 0.01  | 1           | 1000        | gal   |
| 9            | 0.2   | 1           | 3000        | gal   |
| 10           | 1     | 1           | 3000        | gal   |

2.4. Source Geometry Data

In the geometry data window, users can define the geometry of seismic sources. There are different geometrical models implemented in R-CRISIS, in this article only the area source model is used. They are defined as polygons by coordinates for each of their vertexes.

The analyzed sources are:

- Vrancea crustal seismic source – located in South-Eastern Carpathians arc, spread over a stripe area delimited to the north by Pecenega-Camena fault and to the south by the Intramoesian fault [9].
- Vrancea intermediate seismic source – is the Romania’s highest hazardous seismic zone with the epicentral area confined to about 40 x 60 km with most of earthquakes that occur at depths between 60 km and 180 km that are felt over the large areas [10].
- Bârlad depression – located in the North-East of the Vrancea region in the Scythian platform, represents the extension to the North-West of North Dobrogea source zone. The observed earthquakes are of moderate magnitude and do not exceed $M_W = 5.6$ [11].
- Predobrogian Depresion – is part of the southern boundary of the Predobrogian Depression, following alignment of the Sfintul Gheorge fault. From seismotectonic perspective, it is a part of Scythian platform with the maximum observed magnitude of $M_W = 5.3$. 

![Figure 4. The area source geometry.](image-url)
2.5. Seismicity Data
Seismic parameters for all defined seismic sources should be assigned in “Seismicity Data” button. The modified Gutenberg-Richter seismicity model is used to describe every seismic source. This model is associated to Poisson occurrences, so the probability of exceeding intensity level $g$ in the next $T_f$ years, given that an earthquake with magnitude $M$ took place at a distance $R$ from the site, is given by:

$$P_e(g, T_f | M, R) = 1 - \exp[-\Delta\lambda(M)T_f p_1(a|M, R)]$$

(1)

where $p_1(a|M, R)$ is the exceedance probability of intensity level $a$, given that a magnitude $M$ event occurred at a distance $R$ from the site, and $\Delta\lambda(M)$ is the Poissonian magnitude exceedance rate associated to the magnitude range characterized by magnitude $M$.

Table 2. Seismic sources seismicity parameters.

| Seismic source | Vertex number | Coordinates | Average depth | $M_{\text{min}}$ | $M_{\text{max}}$ | $b$ | $\lambda_{M_{\text{min}}}$ | Std of $b$ |
|----------------|---------------|-------------|---------------|-----------------|-----------------|----|--------------------------|-----------|
| VRC            | 1             | 26.823 / 44.870 | 20            | 4.5             | 7.0             | 1.1 | 0.16                     | ±0.20     |
|                | 2             | 27.498 / 45.582 |               |                 |                 |     |                          |           |
|                | 3             | 27.183 / 46.057 |               |                 |                 |     |                          |           |
|                | 4             | 27.084 / 46.116 |               |                 |                 |     |                          |           |
|                | 5             | 26.463 / 45.998 |               |                 |                 |     |                          |           |
|                | 6             | 25.936 / 45.561 |               |                 |                 |     |                          |           |
|                | 7             | 25.793 / 45.174 |               |                 |                 |     |                          |           |
|                | 1             | 26.180 / 45.166 |               |                 |                 |     |                          |           |
|                | 2             | 26.611 / 45.284 |               |                 |                 |     |                          |           |
| VRI            | 3             | 27.100 / 45.893 | 160           | 4.9             | 8.1             | 0.87 | 1.20                     | ±0.08     |
|                | 4             | 26.482 / 46.012 |               |                 |                 |     |                          |           |
|                | 5             | 26.238 / 45.983 |               |                 |                 |     |                          |           |
|                | 6             | 25.955 / 45.307 |               |                 |                 |     |                          |           |
|                | 1             | 27.710 / 45.895 |               |                 |                 |     |                          |           |
|                | 2             | 27.880 / 46.609 |               |                 |                 |     |                          |           |
| DB             | 3             | 27.218 / 46.790 | 10            | 4.5             | 5.8             | 1.10 | 0.07                     | ±0.42     |
|                | 4             | 26.938 / 46.496 |               |                 |                 |     |                          |           |
|                | 5             | 26.867 / 46.197 |               |                 |                 |     |                          |           |
|                | 1             | 29.762 / 44.050 |               |                 |                 |     |                          |           |
|                | 2             | 30.245 / 44.918 |               |                 |                 |     |                          |           |
| DN             | 3             | 27.710 / 45.895 | 10            | 4.5             | 5.8             | 1.84 | 0.06                     | ±0.31     |
|                | 4             | 27.183 / 46.060 |               |                 |                 |     |                          |           |
|                | 5             | 27.498 / 45.582 |               |                 |                 |     |                          |           |
|                | 6             | 27.752 / 45.198 |               |                 |                 |     |                          |           |

2.6. Attenuation Data
Selection of attenuation model is the key step in every seismic hazard assessment. The ground motion prediction models (GMPM) are developed after a lot of research. Generally speaking, the GMPM establishes probabilistic relations between earthquake characteristics, intensities and distances at the computation site.

The attenuation relationship developed by Youngs [12] for subduction zone earthquake is used in case study described in this article. Youngs provides attenuation relationships for rock and soft soils and the relationships are used for estimating both, peak ground acceleration (PGA) and spectral acceleration (SA) for 5% damping value. The attenuation relation for rock site is following:

$$\ln(y) = 0.2418 + 1.414M + C_1 + C_2(10 - M)^3 + C_3 \ln(t_{rup} + 1.7818 \cdot \exp(0.554M)) + 0.00648H + 0.3643z_f$$

(2)
standard deviation is:

$$\sigma = C_4 + C_5M$$  \hspace{1cm} (3)

where $y$ – is PHA or SA in $g$, $M$ – moment magnitude, $r_{rup}$ – closest distance to rupture in km, $H$ – is focal depth in km, $Z_T$ – source type (0 for interface and 1 for interslab) and $\sigma$ – standard deviation.

Based on the research [13] it is decided to use hybrid attenuation models. A hybrid GMPM is the result of the weighted combination of two or more distributions that can have different means values and standard deviations [14]. In general form, the conditional probability of exceeding an intensity measure $A$ is calculated using following relationship [8]:

$$P(A > a) = \sum_{i=1}^{N} w_i \left( 1 - \Phi \left( \frac{a - \mu_i}{\sigma_i} \right) \right)$$  \hspace{1cm} (4)

where $w_i$ is the weight assigned to the $i^{th}$ base GMPM, $\Phi$ – is normal distribution and $\mu_i, \sigma_i$ – are the mean and standard deviation values of the $i^{th}$ base GMPM. For crustal seismic sources are used Cauzzi and Faccioli – CF08 [15] and Akkar and Bommer – AB10 [16] attenuation relationships. The final weighing scheme is given in Table 3.

### Table 3. Weighing scheme for PSHA of the Republic of Moldova.

| GMPM    | Weighting factors |
|---------|-------------------|
| Crustal |
| CF08    | 0.6               |
| AB10    | 0.4               |

3. Results

Having all input information described above in section XX, for all 4 seismic sources that affect the most territory of the Republic of Moldova was computed seismic hazard for the return period of 475 years, which corresponds to the probability of exceedance of 10% in 50 years. The seismic hazard map of the Republic of Moldova in terms of Peak Ground Acceleration and Spectral Acceleration for periods of 0.2 sec and 1 sec as well as spectral acceleration graphs for analysed cities are shown in the figures below. The mean hazard curves for the five analysed cities in the Republic of Moldova is shown in Figure 6.

![Figure 5. Seismic hazard map of the Republic of Moldova (Return Period 475 years).](image-url)
Figure 6. Seismic hazard map of the Republic of Moldova for Spectral Acceleration of 0.2 sec.

Figure 7. Seismic hazard map of the Republic of Moldova for Spectral Acceleration of 1.0 sec.

Figure 8. Mean hazard curves for PGA for the five analyzed cities.

Figure 9. Spectral acceleration for five analyzed cities.

4. Conclusion
In this article is presented a probabilistic seismic hazard assessment of the Republic of Moldova territory. Using R-CRISIS software, firstly developed by professor Mario Ordaz, it was possible to evaluate probabilistically seismic hazard and obtain mean seismic hazard curves as well as spectral acceleration graphs. Wide possibilities of use of R-CRISIS software was shown along with large predefined tools for hazard evaluation. Definitely, the software is useless if key data entered are wrong or missing, therefore to obtain a veridic output one should comprehend the importance of work that lays before software, i.e. identification of seismic sources, determination of seismic parameters for each source, choosing the adequate attenuation law, etc.

5. References
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