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# NONLINEARITIES AND FRACTAL PROPERTIES OF THE EUROPEAN-MEDITERRANEAN SEISMOTECTONIC MODEL

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**Abstract:** This paper presents research results of the study which aim is to reveal and quantitatively describe fractal properties of the European-Mediterranean seismotectonic model applied for seismic hazard assessment of the region under study.

Several seismotectonic provinces are defined, and their nonlinear properties are calculated using both linear elements (boundaries of seismogenic units) and surface areas of the seismogenic units.

The research is conducted on the basis of only formal relationships, not with data on real fault structures or other seismogenic elements, as the relationships have been accepted for seismic hazard calculations by the team of SESAME Project (Project Leader M. Jimenec) and published by Jimenec et al. [*2001*].

Special attention is paid to the Balkan seismotectonic model in order to develop a common seismotectonic model which uses data from the seismic hazard map for a period of 475 years (according the EUROCODE8), that was published in Muco et al. [*2008*].

All the calculations considered only the seismogenic units located in the earth crust, but not deeper seismogenic layers.

It is concluded that most of the seismogenic provinces are similar in their fractal properties, which varied in a narrow range, except for the Adriatic one. The formal approach does not permit to explain these peculiarities.

*Keywords*: Euro-Mediterranean seismotectonics, fractals, nonlinearities.

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# НЕЛИНЕЙНОСТЬ И ФРАКТАЛЬНЫЕ СВОЙСТВА СЕЙСМОТЕКТОНИЧЕСКОЙ МОДЕЛИ ЕВРОПЕЙСКО-СРЕДИЗЕМНОМОРСКОГО РЕГИОНА

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**Аннотация:** В статье представлены результаты исследований, целью которых было установление и количественная оценка фрактальных свойств сейсмотектонической модели Европейско-Средиземноморского региона, по которой была проведена оценка сейсмической опасности для изучаемого региона.

Был выделен ряд сейсмотектонических провинций. Для них определены нелинейные свойства как по линейным элементам (как границам сейсмогенных участков), так и по площадям занимаемых ими поверхностей.

Исследование проведено на базе формальных зависимостей, а не по реальным разломным структурам или другим сейсмогенным элементам, по методу, принятому для расчетов сейсмической опасности группой проекта

SESAME (руководитель M. Jimenec) [*Jimenec et al., 2001*].

Особое внимание уделено сейсмотектонической модели Балканского региона в связи с необходимостью разработки общей сейсмотектонической модели с использованием расчетов по карте сейсмической опасности за период 475 лет (в соответствии с EUROCODE8) по публикации [*Muco et al., 2008*].

Для всех расчетов рассмотрены только сейсмогенные участки, расположенные в земной коре, без учета глубоких сейсмогенных слоев.

Сделан вывод, что большинство сейсмогенных провинций характеризуются сходными фрактальными свойствами, которые варьируются в близком диапазоне, за исключением участка Адриатики. Формальный подход не позволяет найти объяснение таким особенностям.

*Ключевые слова*: сейсмотектоника Европейско-Средиземноморского региона, фракталы, нелинейность.

## INTRODUCTION

The present study is focused to the assessment of the fractal properties and the coefficients of the nonlinear behavior of the spatial distribution of the seismogenic zones in the European and Mediterranean regions. The area is divided into several seismotectonic provinces according to the fragmentation and the specific seismogenic properties of the earth crust for the separated seismic active zones. The used European-Mediterranean seismotectonic model (EMSM) is presented by M. Jimenez et al. [*2001*]. It is targeted to the calculation of the seismic hazard of the investigated region. The separate zones could be characterized by their specific seismogenic properties, which could lead to different seismic impact on buildings and constructions [*Ranguelov et al., 2001*]. In that way this analysis gives the possibility for zone identification and comparison between different seismic provinces, each of them being most probably characterized by specific seismic hazard. It is important to mention that the time scale is not incorporated in this study, thus considering that all seismic events, which can affect the seismic hazard assessment, known from historical times, up to the present days are included. No any information about the faults and their seismogenic properties is incorporated. The deep seismic sources [*Caputo*, *1970*] located deeper the earth crust are also excluded of this study (i.e. Vrancea, Aegean arc, Messina straight and other similar zones with deeper, intermediate seismic sources [*McKenzie, 1972; Papazachos, 1966; Papazachos, 1973*], following the homogeneous approach only to the earth crust located seismic sources.

## METHODOLOGY AND THEORETICAL BASIS

The classical example of a fractal object is defined by [Mandelbrot, 1982]. If the length of an object P is related to the measuring unit length *l* by the formula:

$$P \sim l^{1-D} \tag{1}$$

then P is a fractal and D is a parameter defined as the fractal dimension. This definition was given by B. Mandelbrot in the early 60-s of the 20-th century. His ideas support the view that many objects in nature can not be described by simple geometric forms, and linear dimensions, but they have different levels of geometric fragmentation. It is expressed into the irregularities of the different scales (sizes) – from very small to quite big ones. This makes the measuring unit extremely important parameter, because measuring of the length, the surface or the volume of irregular geometric bodies could be obtained that the measured size could vary hundred to thousand orders. This fact was first determined when measuring the coastal line length of West England and this gave Mandelbrot the idea to define the concept of a fractal.

In geology and geophysics is accepted that definition of the different «fractals» as real physical objects is most often connected to fragmentation [*Korvin, 1992*]. This reveals that each measurable object has a length, surface or volume, which depends on the measuring unit and the object's form irregularity. The smaller the measuring unit is, the bigger is the total value for the linear (surface, volume) dimension of the object and vice versa. The same is valid for 2D and 3D objects.

Another definition of a fractal dimension is related to the serial number of measurement to each of the measuring units used and the object dimensions. If the number of the concrete measurement with a selected linear unit is bigger than r, then it might be presented by:

$$N \sim r^{-D} \tag{2}$$

and the fractal is completely determined by D as its characteristic fractal dimension. Applying this definition for the elements of faulting and faults fragmentation, some authors use this idea to depict formal models of the earth crust fragmentation, which indicates the level of fracturing of the upper earth layers [*Ranguelov, Dimitrova, 2002*].

The theoretical approach for the linear case and for the 2D and 3D cases was developed by [*Turcotte, 1986; Hirata, 1989*]. They focused the attention on the relations between the smallest measuring unit and object's size in analyzing linear (1D), 2D and 3D objects (Fig. 1).

If *l* is the measuring unit and with *m* we denote the obtained value for N at each measuring cycle, then the common sum of the lengths N at level *m* according to [*Turcotte, 1986*] is:

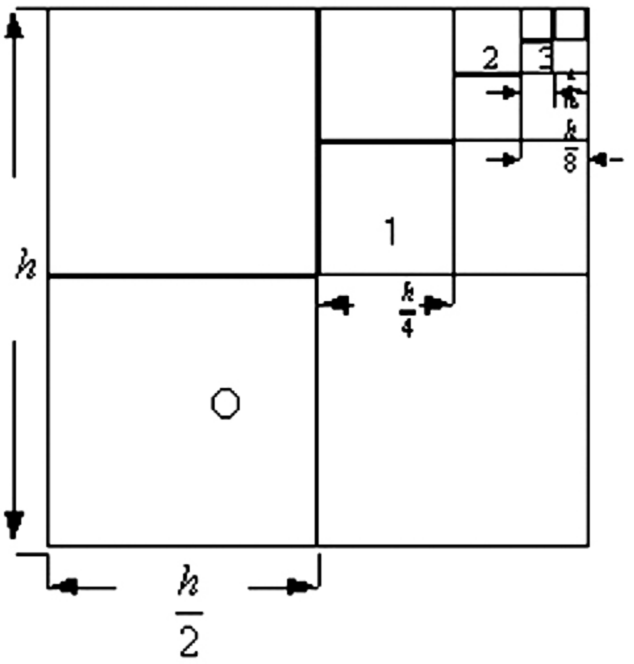


**Fig. 1.** 2D fractal scheme – each linear element is ½ of the larger one.

**Рис. 1.** Двумерная фрактальная схема. Каждый элемент на ½ меньше, чем более крупный.

$$N_m = (1-p_c)(1+\frac{n}{m}p_c+[\frac{n}{m}p_c]^2\ldots[\frac{n}{m}p_c]^m) \quad (3)$$

where *Pc* denotes the probability for measuring of each length for the corresponding cycle of measuring.

Using formulae 1 and 2 we obtain the formulas:

$$\frac{N_{m+1}}{N_m} = 2^D \quad (4)$$

for liner elements, and

$$\frac{N_{m+1}}{N_m} = \left(2^2\right)^D \quad (5)$$

for any area elements (surfaces).

Using this approach we studied the elements of the Mediterranean seismotectonic model. Then analyze the nonlinear behavior and determined the fractal dimensions about both – the linear and surface elements and compare them. The existence of different geometrical objects of similar type like the different seismic hazard zones in various Mediterranean areas makes it suitable to use such an approach, when determining the fractal features of the considered seismotectonic models.

To study the fractal features of the Mediterranean seismotectonic model offered by [*Jimenez et al., 2001*], we have used data from the map (Seismicity Source Regions for the Mediterranean Region). The map scale is 1 : 30000000 – Fig. 2.

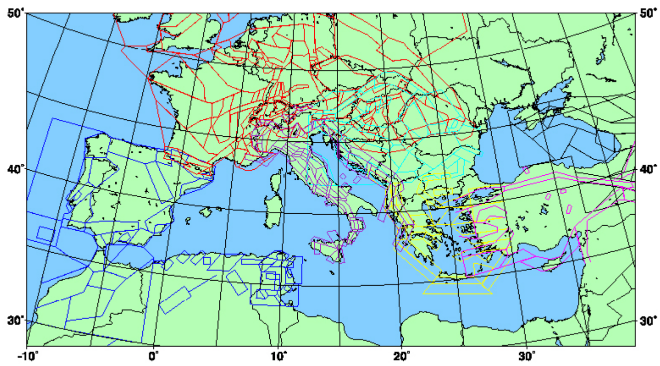


**Fig. 2.** The Euro-Mediterranean seismotectonic model. Seismic provinces are shown by colours. All seismogenic units are considered located in the earth crust. No deeper sources are included.

**Рис. 2.** Сейсмотектоническая модель Европейско-Средиземноморского региона. Сейсмотектонические провинции показаны цветом. Считается, что все изученные сейсмогенные участки располагаются в земной коре. Более глубокие источники не рассматриваются.

The number and the size of all lines delineating each of the surface elements of the model have been determined and graphs plotted. The error of the size determination is less than 5%. The authors of the map also have separated the whole region into several seismotectonic provinces (we follow their denoting):

- The Adriatic (AD)
- Central and West Europe (CWE)
- The Pyrenees and West Africa (PWA)
- Greece (GR)
- Bulgaria and the Northern Balkans (BG NB)

Each province was considered separately at first. Finally general investigation has been done to the whole Euro-Mediterranean region.

The surface fractal dimensions of the separated seismotectonic elements for the same region have been investigated by the same methodology. All surface areas have been determined and the relations - number – area surface for each zone calculated and plotted. The same map by M. Jimenez et al. [*2001*], was used. The scale of the map is 1 : 30000000. The measured surface areas vary from 500 to 2500 km$^2$.

## Results and discussion

The lengths distributions of the linear elements for each seismotectonic cell vary in general between 100-500 km. Cumulative plots have been calculated and presented by the respective fractal dimension to each zone. The results are presented on Fig. 3 (a–f).

By the same way, the hazardous areas have been measured in sq. km. and same graphs plotted. The results are presented on Fig. 4 (a–f).

The obtained results for the different provinces are presented on Table.

The fractal dimension values for the «Adriatic» zone – AD differ substantially from the other zones values.

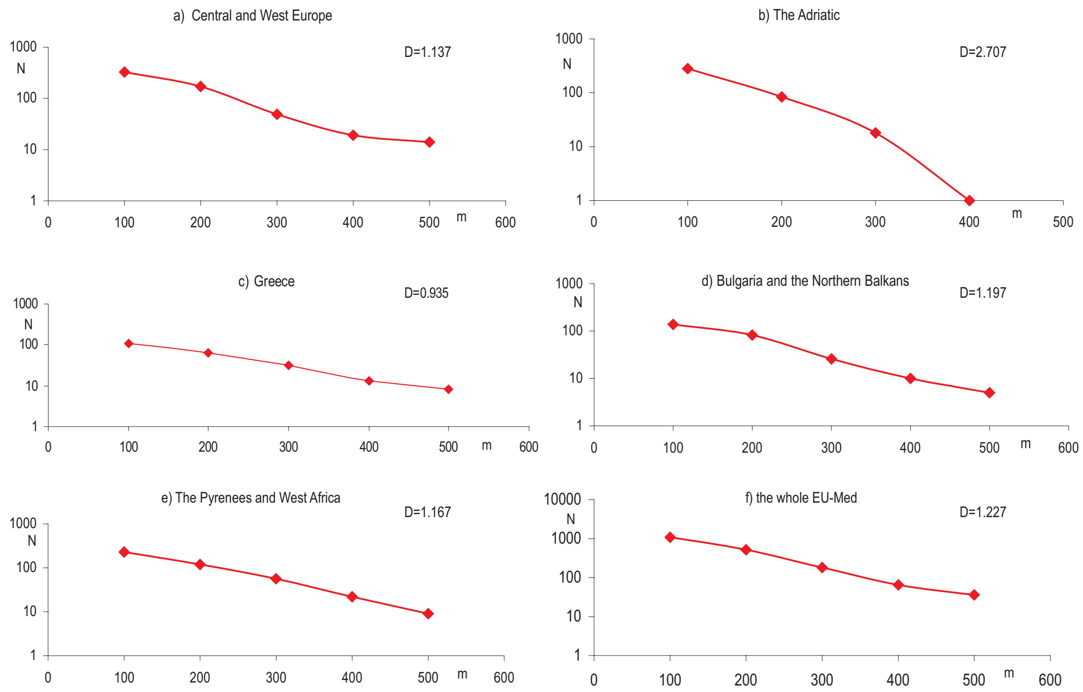


**Fig. 3 (a–f).** Fractal distributions for the studied provinces and their fractal dimensions, D – Linear elements of the seismotectonic model.

**Рис. 3 (a–f).** Фрактальность изученных провинций и фрактальные размерности D по линейным элементам сейсмотектонической модели.

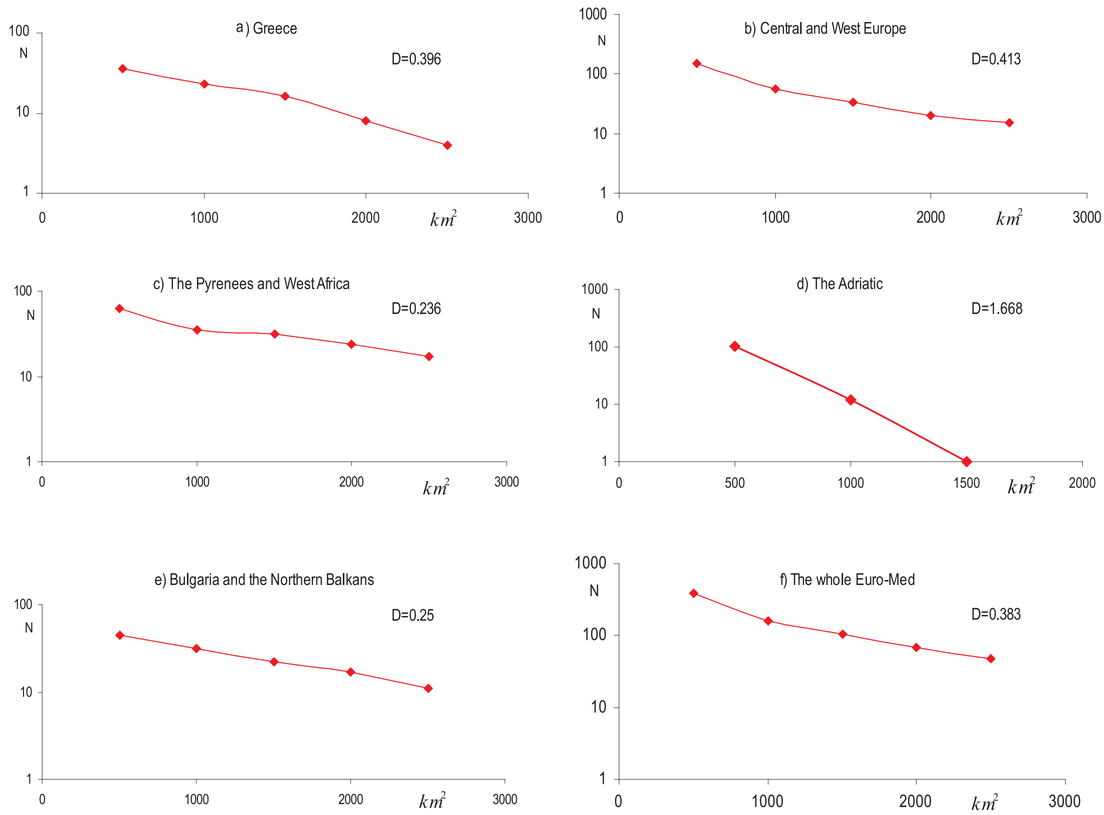


Fig. 4 (a–f). Fractal distributions for the studied seismotectonic model – surface elements.

Рис. 4 (a–f). Фрактальность изученной сейсмотектонической модели по площадным элементам.

**Fractal dimensions about the linear ($D_L$) and surface ($D_S$) elements of the EMSM**

**Фрактальные размерности по линейным ($D_L$) и площадным ($D_S$) элементам сейсмотектонической модели Европейско-Средиземноморского региона (EMSM)**

| Zone | $D_L$ | $D_S$ |
|---|---|---|
| AD | 2.71 | 1.67 |
| CWE | 1.12 | 0.41 |
| PWA | 1.18 | 0.24 |
| GR | 0.94 | 0.40 |
| BG NB | 1.20 | 0.25 |
| All zones | 1.23 | 0.38 |

This concerns both the linear elements and the 2D elements, and thus reflected in both studied parameters of the level of non-linearity (the D-value respectively) being the biggest.

All remaining zones are similar according to their non-linear behavior. The dimension values vary from 1.1 to 1.25 with Greece zone making an exception with a dimension under 1.0 (0.94).

Regarding the 2D fractal features, the differences are smaller with the exception of the Adriatic zone again. Some grouping can be identified as different zones according to their fractal dimension values – «Greece» and «Central and West Europe» (0.41–0.40).

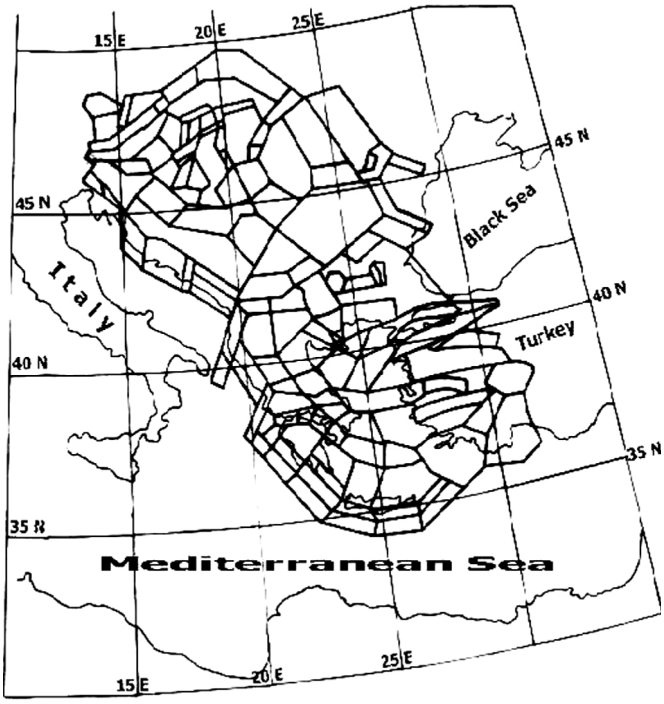


**Fig. 5.** Integrated geometry of surface elements of the seismotectonic model of the Balkan area (after [*Jimenez et al., 2001*], modified [*Ranguelov et al., 2004*]).

**Рис. 5.** Интегрированная геометрия площадных элементов сейсмотектонической модели Балканского региона (по [*Jimenec et al., 2001*] с изменениями [*Ranguelov et al., 2004*]).

These zones are quite different by their seismic activity, but they are similar in their fractality, concerning the sizes of the seismically hazardous areas.

Other similar zones (by their linear dimensions) are «The Pyrenees and West Africa» and «Bulgaria and the Northern Balkans» (0.25–0.24). These provinces have not similar geodynamic features, but they are formally similar according to the distribution of their seismically dangerous areas fractal behavior.

The same methodology has been applied especially about the integrated Balkan seismotectonic model (Fig. 5). It is extracted by the same source [*Jimenec et al., 2001*], due to the need to create the unified Balkan geological hazard map [*Muco et al., 2008*], but the elements of several zones have been separated and integrated to a unified model. The comparison of the results obtained shows that the Balkan model has bigger fractal dimension about the surface elements – D=0.88 (0.38 for the whole Mediterranean) and smaller for the linear elements D= 1.13 (1.23 for the whole Mediterranean area) [*Ranguelov et al.,* 2003, *Ranguelov et al.,* 2004]

The obtained results of this «fractal approach» reveal that the applied method can be useful in comparing the nonlinear behavior of the seismogenic elements of the different seismotectonic provinces. The existence of clearly defined non-linear features of the seismic hazard distribution reveals again, that this sensitive and very important of practical point of view part of the human knowledge to the seismic hazard assessment can not be described by simple (frequently used «by analogy») relationships.

## Conclusions

The fractal analysis is a useful tool to prove the strong nonlinearity concerning the geometry distributions of the seismic active zones. The nonlinear behavior of the elements of the seismotectonic models discovered in this study shows that more punctual and refined methods of the mathematical analysis are obligatory in order to avoid generalizations made only by analogs, which is frequently used method and done in many cases up to now. This can lead sometimes to wrong assessment of the accuracy and representativness and needs sensitivity analysis to avoid errors and wrong conclusions.

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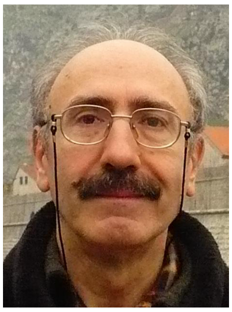

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