

# Determination of intensity attenuation of earthquakes based on probability approach

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**ABSTRACT:** The determination of the spatial distribution of the released energy from the focus to a given point is one of the main tasks and problems to be addressed in the field of seismology and further applied in earthquake engineering and engineering seismology. This problem is known as the attenuation problem, the main task being to determine the size of a given parameter defining the earthquake effects at a given site (intensity, maximum acceleration, velocity or displacement) as a function of the parameters describing the size of earthquake (magnitude, epicentral intensity, released energy, seismic moment) and the distance from the earthquake focus to the site.

## 1 INTRODUCTION

It is known that the intensity scale as one of the possible ways of describing the destructive power of an earthquake is one of the oldest scales that have been used and are still used. This approach is somewhat subjective as to the definition of the intensity level, especially with the first intensity scale. However, the definition of new scales, i.e., the innovation and the modification of the old scales and the most recent crucial empirical knowledge have reduced this subjectivity element to a minimum. Although this element can be considered as a disadvantage, the number of data on occurred earthquakes given in the intensity scale and the isoseismal maps or, descriptively, for a certain historic earthquake exceeds the number of instrumental data which enables a probabilistic statistic analysis. The first attenuation curves in seismology are therefore defined in respect to the intensity. The advantage of using such type of data is the longer period of their observation in comparison with the instrumental data. There is also a possibility to establish an empirical correlation between intensity and amplitude of the recorded strong ground motion (acceleration, velocity or displacement) at a certain site on the basis of the obtained distribution of intensity depending on distance.

## 2 DATABASE

The determination and definition of input data for each and this investigation depends on the formulation of the problem

itself. This means that the formulation of the problem of obtaining an attenuation of seismic intensity initiates the use of macroseismic data as input data. Their determination is of a great importance for obtaining the distribution of intensity in areas of possible destructive strong ground motions.

The investigation of the seismicity of a certain area based exclusively on seismic information does not give satisfying results. Therefore, additional geological, geodetic, gravimetric and other data are required. Along with the seismological data, these data enable a thorough insight into the seismic phenomena. There are general criteria of how to consider the additional data in combination with the seismological data. However, there isn't a generally accepted methodology of applying these criteria in the consideration of the quantitative parameters of seismic activity.

Starting from the well known fact that there is a connection between the seismic activity and the defined faults on the territory of Yugoslavia, i.e., the earthquakes occurring on this territory are the result of the tectonic activity of earthquake foci located in the earth's crust, and also taking into account the previously mentioned fact about the existence of longitudinal faults, the territory of Yugoslavia has been divided into two regions - MS and OS. The stretching of the longitudinal faults is presented on the neotectonic map (D. Skoko, M. Arsovski, D. Hadzиеvski, 1975).

Apart from this division made in respect to similar geotectonic structures, there is an additional division in respect to the focal depth. According to the second division, there are two groups of earthquakes: earthquakes

occurring at a depth of less than or equal to 10 km and earthquakes occurring at a depth of over 10 km. In this way, the main data-bases were formed, i.e., isoseismal maps used in the analyses, as follows:

- 1 Data on earthquakes occurring on the whole territory of Yugoslavia;
- 2 Data on earthquakes that occurred on the whole territory of Yugoslavia with  $h > 10$  km;
- 3 Data on earthquakes that occurred on the whole territory of Yugoslavia with  $h \leq 10$  km.
- 4 Data on earthquakes that occurred in the MS region;
- 5 Data on earthquakes that occurred in the OS region;

### 3 THEORY

The earthquake phenomenon and its manifestation upon the surface are complex physical processes. It is therefore impossible to establish a more consistent deterministic model to describe the individual aspects of the earthquake phenomena as is the intensity attenuation. Hence, the statistical analysis approach and the probabilistic modeling represent the only appropriate approach that will provide, perhaps not so detailed, but consistent information in the first approximation, that will be sufficient for drawing further conclusions.

The input data on the epicentral distances depending on epicentral intensity  $I_0$  and the difference  $\Delta I = I_0 - I_1$  used in the analysis performed within this investigation have an empirical distribution function of the following form:

$$\Pr\{R < R_{i+1} | I_0\} = i / N(I_0, \Delta I), \quad R_i < R < R_{i+1} \dots (1)$$

$$\Pr\{\log R = x, \Delta I | I_0\} = \frac{1}{\sigma(I_0, \Delta I)} \sqrt{\frac{1}{2\pi}} \int_{-\infty}^{\log R} \exp\left\{-\frac{1}{2} \left[\frac{m(I_0, \Delta I) - x}{\sigma(I_0, \Delta I)}\right]^2\right\} dx \dots (2)$$

Applying the theoretical Gauss' distribution, this assumed approximation of empirical data can be explained as follows: if a random value is normally distributed, it remains normally distributed after each linear transformation for which it was used (including also differentiation and integration). However, there is another reason and that is the law on the normal distribution that is really very frequent in nature. According to the central ultimate theorem, the normal distribution (or a distribution close to the normal distribution) is characteristic for those random values that are formed as a result of a large number of independent causes each of which having a little influence if taken separately.

### 4 PRESENTATION OF THE RESULTS

The probabilistic method of analysis was applied for all the five groups of data. The results are presented in a tabular form and graphically whereby five sets of tabular-graphic results are obtained. These results were used for discussion and critical review of the applied methodology and model.

Presented in Tables 3.1 from a) to e) are the statistic parameters of earthquakes for the analyzed data set. These tables also show the number of included isoseismal maps (the upper values) and the number of data obtained by drawing 16 radii (the lower values) for each combination of  $I_0$  and  $\Delta I$ .

Table 3.1. Number of earthquakes and number of data N ( $I_0, \Delta I$ )

- a) for Yugoslavia
- b) for Yugoslavia with focal depth  $h > 10$  km
- c) for Yugoslavia with focal depth  $h \leq 10$  km
- d) for region MS
- e) for region OS

| $I_0 \backslash \Delta I$ | 0         | 1         | 2         | 3         | 4         | 5       | 6       |
|---------------------------|-----------|-----------|-----------|-----------|-----------|---------|---------|
| 5                         | 10<br>145 | 8<br>97   | 5<br>55   |           |           |         |         |
| 6                         | 54<br>765 | 54<br>737 | 47<br>505 | 7<br>107  |           |         |         |
| 7                         | 40<br>531 | 37<br>587 | 36<br>513 | 25<br>249 | 7<br>69   |         |         |
| 8                         | 17<br>253 | 17<br>259 | 17<br>228 | 15<br>170 | 12<br>120 | 6<br>50 |         |
| 9                         | 4<br>60   | 4<br>64   | 4<br>37   | 2<br>29   | 1<br>16   | 1<br>11 | 1<br>1  |
| 10                        | 2<br>16   | 2<br>25   | 2<br>25   | 1<br>16   | 1<br>16   | 1<br>16 | 1<br>16 |

a)

| $I_0 \backslash \Delta I$ | 0         | 1         | 2         | 3       | 4       | 5       | 6      |
|---------------------------|-----------|-----------|-----------|---------|---------|---------|--------|
| 5                         | 10<br>145 | 8<br>97   |           |         |         |         |        |
| 6                         | 28<br>374 | 28<br>371 | 24<br>231 |         |         |         |        |
| 7                         | 8<br>86   | 8<br>96   | 8<br>76   | 4<br>42 |         |         |        |
| 8                         | 5<br>77   | 5<br>77   | 5<br>55   | 4<br>42 | 3<br>30 |         |        |
| 9                         | 2<br>44   | 2<br>48   | 2<br>28   | 2<br>24 | 1<br>16 | 1<br>11 |        |
| 10                        | 1<br>16   | 1<br>16   | 1<br>16   | 1<br>16 | 1<br>16 | 1<br>16 | 1<br>4 |

b)

| $I_0 \backslash \Delta I$ | 0         | 1         | 2         | 3         | 4       | 5 | 6 |
|---------------------------|-----------|-----------|-----------|-----------|---------|---|---|
| 5                         |           |           |           |           |         |   |   |
| 6                         | 34<br>391 | 34<br>366 | 23<br>274 |           |         |   |   |
| 7                         | 26<br>461 | 26<br>491 | 25<br>437 | 20<br>207 |         |   |   |
| 8                         | 12<br>176 | 12<br>182 | 11<br>173 | 10<br>128 | 7<br>90 |   |   |
| 9                         | 1<br>16   | 1<br>16   | 1<br>9    | 1<br>5    |         |   |   |
| 10                        |           | 1<br>9    | 1<br>9    |           |         |   |   |

c)

| $\Delta I$<br>$I_0$ | 0   | 1   | 2   | 3   | 4  | 5  | 6 |
|---------------------|-----|-----|-----|-----|----|----|---|
| 5                   | 3   | 2   |     |     |    |    |   |
|                     | 48  | 32  |     |     |    |    |   |
| 6                   | 24  | 23  | 19  |     |    |    |   |
|                     | 373 | 367 | 289 |     |    |    |   |
| 7                   | 20  | 20  | 18  | 8   |    |    |   |
|                     | 320 | 319 | 281 | 116 |    |    |   |
| 8                   | 7   | 7   | 6   | 5   | 3  |    |   |
|                     | 109 | 99  | 87  | 65  | 43 |    |   |
| 9                   | 2   | 2   | 2   | 2   | 1  | 1  |   |
|                     | 28  | 32  | 23  | 24  | 16 | 11 |   |
| 10                  | 2   | 2   | 2   | 2   | 2  | 2  | 1 |
|                     | 16  | 16  | 16  | 16  | 16 | 16 | 4 |

d)

| $\Delta I$<br>$I_0$ | 0   | 1   | 2   | 3   | 4  | 5 | 6 |
|---------------------|-----|-----|-----|-----|----|---|---|
| 5                   | 8   | 7   |     |     |    |   |   |
|                     | 113 | 81  |     |     |    |   |   |
| 6                   | 28  | 27  | 15  |     |    |   |   |
|                     | 389 | 386 | 216 |     |    |   |   |
| 7                   | 18  | 18  | 14  | 18  | 3  |   |   |
|                     | 227 | 252 | 220 | 126 | 43 |   |   |
| 8                   | 8   | 8   | 8   | 5   | 4  | 1 |   |
|                     | 96  | 112 | 96  | 73  | 50 | 6 |   |
| 9                   | 1   | 1   |     |     |    |   |   |
|                     | 9   | 9   |     |     |    |   |   |
| 10                  |     |     |     |     |    |   |   |

e)

Tables 3.2 from a) to e) show the main deviation  $m(I_0, \Delta I)$ , the upper values and the standard deviation  $\sigma(I_0, \Delta I)$ , the lower values, that represent parameters of the assumed normal distribution of the possible combinations of  $I_0$  and  $\Delta I$ . The meaning of these parameters can be illustrated by concrete values. For instance, taking into consideration that the theoretical distribution is defined in respect to  $\log_{10} R$ , the values of  $I_0 = 7$  and  $\Delta I = 2$ ,  $m(7, 2) = 1.4822$  and  $\sigma(7, 2) = 0.2378$  given in Table 3.2 mean that if an earthquake with an epicentral intensity of  $I_0 = 7$  takes place on the territory of Yugoslavia, an intensity of  $I < 5$  might be expected at  $R = 30.3$  km ( $+ 10^{1.4822}$ ) with a mean error of  $\pm 1.7$  km ( $> 10^{0.2378}$ ).

Tables 3.3 from a) to e) show the parameter of the Kolmogorov-Smirnov's statistic, i.e., the maximum values,  $\mathcal{E}(I_0, \Delta I)$  and the critical values of this test,  $\mathcal{E}_{ks}(I_0, \Delta I)$  - the minimum values. These two values determine which of the distribution can be accepted ( $\mathcal{E} < \mathcal{E}_{ks}$ ), i.e., rejected ( $\mathcal{E} > \mathcal{E}_{ks}$ ) for a significance level of up to 95%.

Table 3.2 Mean value  $m(I_0, \Delta I)$  and standard deviation  $\sigma(I_0, \Delta I)$ , according to Gauss' distribution

- a) for Yugoslavia earthquakes
- b) for Yugoslavia earthquakes with focal depth  $h > 10$  km
- c) for Yugoslavia earthquakes with focal depth  $h \leq 10$  km
- d) for earthquakes of region MS
- e) for earthquakes of region OS

| $\Delta I$<br>$I_0$ | 0      | 1      | 2      | 3      | 4      | 5      | 6      |
|---------------------|--------|--------|--------|--------|--------|--------|--------|
| 5                   | 1.2112 | 1.6992 | 2.0306 |        |        |        |        |
|                     | 0.3330 | 0.0670 | 0.1604 |        |        |        |        |
| 6                   | 0.9813 | 1.3772 | 1.6391 | 1.7529 |        |        |        |
|                     | 0.3430 | 0.2677 | 0.2441 | 0.2054 |        |        |        |
| 7                   | 0.8579 | 1.2337 | 1.4822 | 1.6611 | 1.8601 |        |        |
|                     | 0.2754 | 0.2361 | 0.2378 | 0.2300 | 0.2209 |        |        |
| 8                   | 0.9084 | 1.2748 | 1.5561 | 1.7217 | 1.9256 | 2.1434 |        |
|                     | 0.3345 | 0.3060 | 0.3088 | 0.2720 | 0.2416 | 0.1622 |        |
| 9                   | 0.8628 | 1.3054 | 1.6510 | 1.8558 | 1.9789 | 2.1957 |        |
|                     | 0.2824 | 0.2070 | 0.2120 | 0.1595 | 0.0931 | 0.0844 |        |
| 10                  | 0.7822 | 1.1437 | 1.4101 | 1.6001 | 1.8004 | 2.0644 | 2.4829 |
|                     | 0.2491 | 0.2319 | 0.1869 | 0.1321 | 0.0926 | 0.0886 | 0.0230 |

a)

| $\Delta I$<br>$I_0$ | 0      | 1      | 2      | 3      | 4      | 5      | 6      |
|---------------------|--------|--------|--------|--------|--------|--------|--------|
| 5                   | 1.2122 | 1.6982 |        |        |        |        |        |
|                     | 0.3310 | 0.2184 |        |        |        |        |        |
| 6                   | 1.1275 | 1.5318 | 1.7879 |        |        |        |        |
|                     | 0.2888 | 0.2068 | 0.1962 |        |        |        |        |
| 7                   | 0.8687 | 1.4689 | 1.7771 | 1.3198 |        |        |        |
|                     | 0.3927 | 0.1668 | 0.1742 | 0.1015 |        |        |        |
| 8                   | 1.0283 | 1.4182 | 1.6798 | 1.8384 | 2.0417 |        |        |
|                     | 0.3621 | 0.2816 | 0.2798 | 0.2869 | 0.2857 |        |        |
| 9                   | 0.8949 | 1.3003 | 1.5850 | 1.8232 | 1.9789 | 2.1957 |        |
|                     | 0.3053 | 0.2353 | 0.1984 | 0.1514 | 0.0931 | 0.0840 |        |
| 10                  | 0.7822 | 1.1961 | 1.4365 | 1.6003 | 1.8001 | 2.0611 | 2.3462 |
|                     | 0.2491 | 0.1549 | 0.1491 | 0.1321 | 0.0926 | 0.0881 | 0.0231 |

b)

| $\Delta I$<br>$I_0$ | 0      | 1      | 2      | 3      | 4      | 5 | 6 |
|---------------------|--------|--------|--------|--------|--------|---|---|
| 5                   |        |        |        |        |        |   |   |
| 6                   | 0.8381 | 1.2205 | 1.5137 |        |        |   |   |
|                     | 0.3407 | 0.2285 | 0.2085 |        |        |   |   |
| 7                   | 0.8289 | 1.1878 | 1.4309 | 1.6087 |        |   |   |
|                     | 0.2817 | 0.2198 | 0.2083 | 0.2126 |        |   |   |
| 8                   | 0.8559 | 1.2142 | 1.5168 | 1.6912 | 1.8934 |   |   |
|                     | 0.3083 | 0.2961 | 0.3080 | 0.2513 | 0.1992 |   |   |
| 9                   | 0.7747 | 1.3207 | 1.8565 | 2.0124 |        |   |   |
|                     | 0.1877 | 0.0782 | 0.0812 | 0.0960 |        |   |   |
| 10                  |        | 1.0505 | 1.3632 |        |        |   |   |
|                     |        | 0.3180 | 0.2434 |        |        |   |   |

c)

| $\Delta I$<br>$I_0$ | 0      | 1      | 2      | 3      | 4      | 5      | 6      |
|---------------------|--------|--------|--------|--------|--------|--------|--------|
| 5                   | 1.0981 | 1.5855 |        |        |        |        |        |
|                     | 0.3021 | 0.1431 |        |        |        |        |        |
| 6                   | 0.9229 | 1.3269 | 1.5849 |        |        |        |        |
|                     | 0.3680 | 0.2872 | 0.2524 |        |        |        |        |
| 7                   | 0.7920 | 1.2099 | 1.4313 | 1.5983 |        |        |        |
|                     | 0.3394 | 0.2196 | 0.2215 | 0.2428 |        |        |        |
| 8                   | 0.7974 | 1.2389 | 1.4891 | 1.6925 | 1.8938 |        |        |
|                     | 0.3169 | 0.2785 | 0.3067 | 0.2501 | 0.2121 |        |        |
| 9                   | 1.0784 | 1.4366 | 1.6554 | 1.8232 | 1.9789 | 2.1957 |        |
|                     | 0.1807 | 0.1608 | 0.1368 | 0.1514 | 0.0930 | 0.845  |        |
| 10                  | 0.7822 | 1.1961 | 1.4365 | 1.6001 | 1.8004 | 2.0644 | 2.3462 |
|                     | 0.2492 | 0.1549 | 0.1490 | 0.1320 | 0.0920 | 0.0881 | 0.0232 |

d)

| $\Delta I$<br>$I_0$ | 0      | 1      | 2      | 3      | 4      | 5      | 6 |
|---------------------|--------|--------|--------|--------|--------|--------|---|
| 5                   | 1.2015 | 1.6865 |        |        |        |        |   |
|                     | 0.2950 | 0.2294 |        |        |        |        |   |
| 6                   | 1.0267 | 1.4371 | 1.7117 |        |        |        |   |
|                     | 0.3180 | 0.2369 | 0.2141 |        |        |        |   |
| 7                   | 0.7914 | 1.2447 | 1.5285 | 1.7114 | 1.7149 |        |   |
|                     | 0.3624 | 0.2412 | 0.2321 | 0.2080 | 0.1463 |        |   |
| 8                   | 1.0075 | 1.2802 | 1.5594 | 1.7295 | 1.9455 | 2.2900 |   |
|                     | 0.3514 | 0.3340 | 0.3075 | 0.3024 | 0.2633 | 0.0812 |   |
| 9                   | 0.5736 | 1.0276 |        |        |        |        |   |
|                     | 0.1881 | 0.0337 |        |        |        |        |   |
| 10                  | 1.0505 | 1.3632 |        |        |        |        |   |
|                     | 0.3180 | 0.2434 |        |        |        |        |   |

e)

Tables 3.3 Statistics  $\mathcal{E}(I_0, \Delta I)$  and critical value,  $\mathcal{E}_{ks}(I_0, \Delta I)$  after Kolmogorov-Smirnov's test

- a) for Yugoslavia earthquakes

- b) for Yugoslavia earthquakes  $h > 10$  km
- c) for Yugoslavia earthquakes  $h \leq 10$  km
- d) for earthquakes of region MS
- e) for earthquakes of region OS

| $\Delta l$<br>$l_0$ | 0      | 1      | 2      | 3      | 4      | 5      | 6      |
|---------------------|--------|--------|--------|--------|--------|--------|--------|
| 5                   | 0.0564 | 0.0670 | 0.0906 |        |        |        |        |
|                     | 0.1229 | 0.1380 | 0.1803 |        |        |        |        |
| 6                   | 0.0904 | 0.0654 | 0.0507 | 0.0983 |        |        |        |
|                     | 0.0492 | 0.0501 | 0.0605 | 0.1315 |        |        |        |
| 7                   | 0.0979 | 0.0610 | 0.0582 | 0.0650 | 0.1524 |        |        |
|                     | 0.0590 | 0.0561 | 0.0601 | 0.0881 | 0.1609 |        |        |
| 8                   | 0.0521 | 0.0573 | 0.0488 | 0.0379 | 0.0593 | 0.0724 |        |
|                     | 0.0855 | 0.0845 | 0.0900 | 0.1043 | 0.1242 | 0.1884 |        |
| 9                   | 0.0549 | 0.1251 | 0.1066 | 0.0982 | 0.1039 | 0.1230 |        |
|                     | 0.1723 | 0.1673 | 0.2196 | 0.2439 | 0.3113 | 0.3945 |        |
| 10                  | 0.2043 | 0.0843 | 0.0879 | 0.1804 | 0.1338 | 0.1393 | 0.1388 |
|                     | 0.3113 | 0.2639 | 0.2639 | 0.3113 | 0.3113 | 0.3113 | 0.7078 |

a)

| $\Delta l$<br>$l_0$ | 0      | 1      | 2      | 3      | 4      | 5      | 6      |
|---------------------|--------|--------|--------|--------|--------|--------|--------|
| 5                   | 0.0564 | 0.0670 |        |        |        |        |        |
|                     | 0.1129 | 0.1381 |        |        |        |        |        |
| 6                   | 0.0922 | 0.0640 | 0.0898 |        |        |        |        |
|                     | 0.0703 | 0.0706 | 0.0895 |        |        |        |        |
| 7                   | 0.1661 | 0.0800 | 0.1527 | 0.1433 |        |        |        |
|                     | 0.1446 | 0.1369 | 0.1536 | 0.2058 |        |        |        |
| 8                   | 0.0766 | 0.0544 | 0.1384 | 0.1862 | 0.1652 |        |        |
|                     | 0.1526 | 0.1526 | 0.1804 | 0.2058 | 0.2417 |        |        |
| 9                   | 0.1059 | 0.1801 | 0.1086 | 0.0987 | 0.1039 | 0.1230 |        |
|                     | 0.2014 | 0.2014 | 0.1927 | 0.2595 | 0.3288 | 0.3945 |        |
| 10                  | 0.2043 | 0.1284 | 0.1250 | 0.1804 | 0.1338 | 0.1393 | 0.1388 |
|                     | 0.3288 | 0.3288 | 0.3288 | 0.3288 | 0.3288 | 0.3288 | 0.6239 |

b)

| $\Delta l$<br>$l_0$ | 0      | 1      | 2      | 3      | 4      | 5 | 6 |
|---------------------|--------|--------|--------|--------|--------|---|---|
| 5                   | 0.0807 | 0.0686 | 0.0566 |        |        |   |   |
|                     | 0.0688 | 0.0711 | 0.0822 |        |        |   |   |
| 6                   | 0.0969 | 0.0724 | 0.0748 | 0.0909 |        |   |   |
|                     | 0.0633 | 0.0614 | 0.0651 | 0.0945 |        |   |   |
| 7                   | 0.0909 | 0.0712 | 0.0757 | 0.0910 | 0.0683 |   |   |
|                     | 0.2033 | 0.1008 | 0.1162 | 0.1202 | 0.1412 |   |   |
| 8                   | 0.1858 | 0.1440 | 0.3295 | 0.2517 |        |   |   |
|                     | 0.3288 | 0.3288 | 0.4346 | 0.5633 |        |   |   |
| 9                   | 0.2499 | 0.2439 | 0.2439 |        |        |   |   |
|                     | 0.4396 | 0.4396 |        |        |        |   |   |

c)

| $\Delta l$<br>$l_0$ | 0      | 1      | 2      | 3      | 4      | 5      | 6      |
|---------------------|--------|--------|--------|--------|--------|--------|--------|
| 5                   | 0.0975 | 0.0745 |        |        |        |        |        |
|                     | 0.1927 | 0.2354 |        |        |        |        |        |
| 6                   | 0.1226 | 0.0757 | 0.0728 |        |        |        |        |
|                     | 0.0704 | 0.0710 | 0.0800 |        |        |        |        |
| 7                   | 0.1286 | 0.0773 | 0.1023 | 0.1088 |        |        |        |
|                     | 0.0760 | 0.0761 | 0.0811 | 0.1263 |        |        |        |
| 8                   | 0.0611 | 0.1197 | 0.1226 | 0.0970 | 0.1093 |        |        |
|                     | 0.1303 | 0.1347 | 0.1437 | 0.1660 | 0.2036 |        |        |
| 9                   | 0.0760 | 0.0644 | 0.1054 | 0.0987 | 0.1039 | 0.1230 |        |
|                     | 0.2506 | 0.2354 | 0.2759 | 0.2699 | 0.3288 | 0.3945 |        |
| 10                  | 0.2043 | 0.1284 | 0.1250 | 0.1804 | 0.1338 | 0.1393 | 0.1388 |
|                     | 0.3288 | 0.3288 | 0.3288 | 0.3288 | 0.3288 | 0.3288 | 0.6239 |

d)

| $\Delta l$<br>$l_0$ | 0      | 1      | 2      | 3      | 4      | 5      | 6 |
|---------------------|--------|--------|--------|--------|--------|--------|---|
| 5                   | 0.0500 | 0.0839 |        |        |        |        |   |
|                     | 0.1279 | 0.1488 |        |        |        |        |   |
| 6                   | 0.0686 | 0.0491 | 0.0339 |        |        |        |   |
|                     | 0.0689 | 0.0692 | 0.0925 |        |        |        |   |
| 7                   | 0.1323 | 0.0750 | 0.0424 | 0.0450 | 0.1063 |        |   |
|                     | 0.0903 | 0.0857 | 0.0917 | 0.1212 | 0.2036 |        |   |
| 8                   | 0.0651 | 0.1080 | 0.0619 | 0.0793 | 0.1680 | 0.2190 |   |
|                     | 0.1369 | 0.1285 | 0.1369 | 0.1567 | 0.1884 | 0.5324 |   |
| 9                   | 0.1765 | 0.2939 |        |        |        |        |   |
|                     | 0.3288 | 0.3288 |        |        |        |        |   |
| 10                  | 0.2499 | 0.2439 | 0.2439 |        |        |        |   |
|                     | 0.4396 | 0.4396 |        |        |        |        |   |

e)

The tables are followed by graphical results from the performed analysis for all the five data sets taken separately according to the following order:

i) Empirical distribution function with an epicentral intensity determined as a function of  $\log R$  (distance from the epicentre) and test of significance, Figures 3.1 and 3.2.

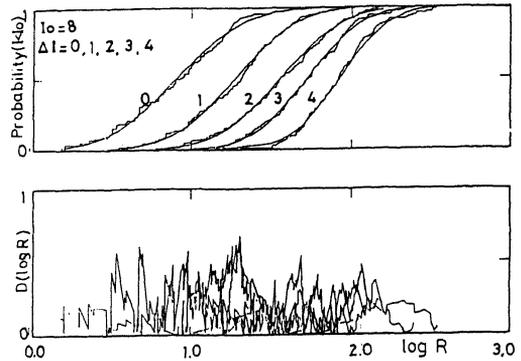


Figure 3.1 Cumulative distribution function versus  $\log R$  i.e. the staircase function represent  $Pr_{\Delta l, l_0}(\log R)$  determined directly from the data for  $l_0 = 8$  and  $\Delta l = 0, 1, 2, 3, 4$ , while the smooth curve is the corresponding normal distribution  $Pr_{\Delta l, l_0}(\log R)$ . Bottom: the error random variable  $D_{\Delta l, l_0}(\log R)$  shows the difference between  $Pr_{\Delta l, l_0}(\log R)$  and  $Pr_{\Delta l, l_0}(\log R)$  normalized to the Kolmogorov-Smirnov's test for confidence level  $\alpha = 95\%$  (this example is for case when all earthquakes are used).

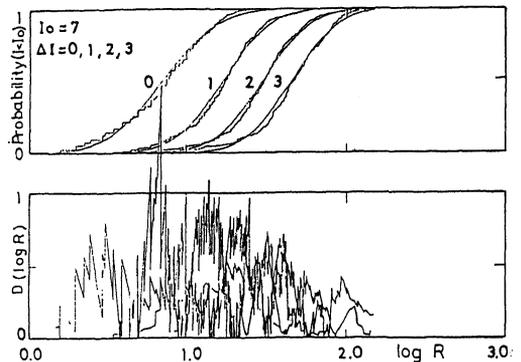


Figure 3.2 Cumulative distribution function versus  $\log R$  i.e. the staircase function represent  $Pr_{\Delta l, l_0}(\log R)$  determined directly from the data for  $l_0 = 7$  and  $\Delta l = 0, 1, 2, 3$ , while the smooth curve is the corresponding normal distribution  $Pr_{\Delta l, l_0}(\log R)$ . Bottom: the error random variable  $D_{\Delta l, l_0}(\log R)$  shows the difference between  $Pr_{\Delta l, l_0}(\log R)$  and  $Pr_{\Delta l, l_0}(\log R)$  normalized to the Kolmogorov-Smirnov's test for confidence level  $\alpha = 95\%$  (this example is for case when all earthquakes are used).

Intensity attenuation depending on epicentral distance. Presented is the relationship between the mean value of the Gauss's distribution and  $\log R$  (distance from isoseismal) for an epicentral intensity of 5 to 10; Figures 3.3 to 3.7.

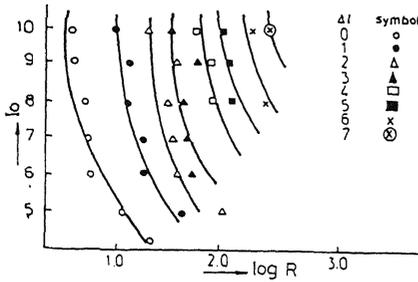


Figure 3.3 Dependences of  $\Delta I$  values on the epicentral intensity  $I_0$  and logarithmic of distance  $R$  for all earthquakes of the territory of Yugoslavia.

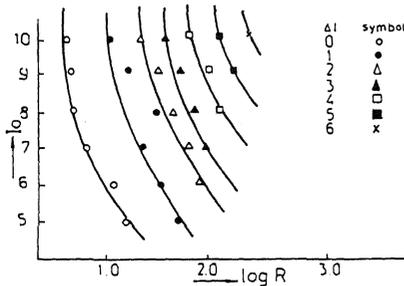


Figure 3.4 Dependences of  $\Delta I$  values on the epicentral intensity  $I_0$  and logarithmic of distance  $R$  for all earthquakes with focal depth  $h > 10$  km, for the whole territory of Yugoslavia.

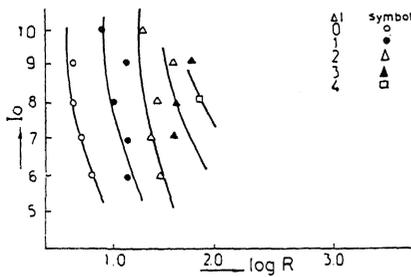


Figure 3.5 Dependences of  $\Delta I$  values of the epicentral intensity  $I_0$  and logarithmic of distance  $R$  for all earthquakes of focal depth  $h \leq 10$  km, for the whole territory of Yugoslavia.

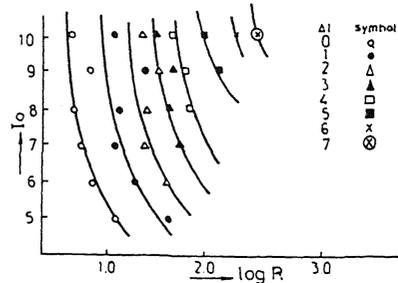


Figure 3.6 Dependences of  $\Delta I$  values on the epicentral intensity  $I_0$  and logarithmic of distance  $R$  for all earthquakes of region MS.

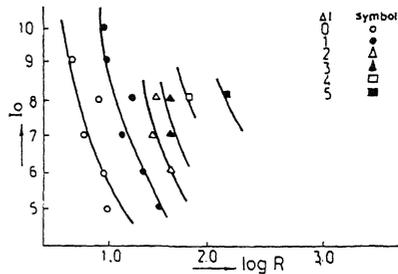


Figure 3.7 Dependences of  $\Delta I$  values on the epicentral intensity  $I_0$  and logarithmic of distance  $R$  for all earthquakes of region OS.

#### 5 ANALYSIS AND DISCUSSION OF THE RESULTS

On the basis of the performed statistic tests, it is concluded that in most of the cases the test gives satisfying results at an acceptability level of 95%. In several cases, the test showed that  $D(R) > 1$  which means that the assumed theoretical distribution has to be rejected. It is interesting to note that in all the five analyses there is a certain regularity, namely, the combinations of  $I_0=7, \Delta I=0$  and  $I_0=6, \Delta I=0$  lead to an unsatisfying outcome of the statistic test. Taking into account that the statistic test gives satisfying results for other combinations of  $I_0, \Delta I$ , this regularity speaks for itself that some other reasons other the inadequacy of the theoretical distribution are responsible for the unsatisfying outcome of certain tests. It is, therefore, asserted a lot of certainty that the normal distribution of  $\log R$  is an acceptable probabilistic model for intensity attenuation.

It can be noticed that at larger distances, the standard deviation tends to lower values, the maximum standard deviation being  $m=1.0$  for all five data sets which is of a vague significance. The decrease of  $G(I_0, \Delta I)$  with increase of  $m(I_0, \Delta I)$  has a physical explanation, namely, the increase of  $m(I_0, \Delta I)$  leads to lower intensity values whereby the isoseismal acquire an approximately

round shape and distances measured from the epicentre at the 16 radial directions are slightly differentiated.

## 6 CONCLUSIONS AND RECOMMENDATIONS

The attenuation function defines the distribution of seismic intensity that according to its physical determination represents the seismic effect upon the surface. For the purpose of defining the attenuation function a probabilistic approach in analysis has been applied for the mathematical model of an assumed distribution function (Chapter 3). Isoseismal maps have been used to provide data for the analysis. This enabled estimation of intensity on the basis of known epicentral intensity and distance from the epicentre.

The obtained results on the intensity of attenuation for both groups that were classified in respect to the focal depth are not so differentiated as was expected on the basis of the theoretical assumptions regarding the seismic wave propagation.

The definition of the probabilistic models of intensity attenuation gives a possibility of a more consistent analysis of the hazard and risk on a purely probabilistic basis. Namely, it is known that the isoseismals of equal values of some hazard parameters are drawn on the basis of deterministic attenuation covers. The only probabilistic element is included via the stochastic modeling of the earthquake occurrence at a given focus.

The probabilistic attenuation models are a progressive step closer to the definition of a total probabilistic model of the seismic hazard.

This model can certainly be improved if the azimuth is included as an independent variable. In this way, included in the probabilistic attenuation will be also the anisotropy and the geological inhomogeneities in different directions that have an effect upon the attenuation of seismic energy.

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