GEOLOGIJA *30*, 391–409 (1987), Ljubljana

UDK 550.34.01:550.343.42(497.12) = 20

A simple macroseismic attenuation model

Enostaven makroseizmičen atenuacijski model

Janez Lapajne
Seizmološki zavod SR Slovenije, Kersnikova 3, 61000 Ljubljana

Abstract

A simple macroseismic attenuation model for an observed intensity I (MSK-78 intensity scale is used) and a "macroseismic" ground acceleration a can be defined by a system of three linear equations of the type I = f (log r) and log a = f (log r), where r is the epicentral distance (which can be a distance from the epicenter to an isoseismal contour in an arbitrary direction, a radius of a circle of equivalent area, or, generally, a distance from the epicenter to any site). Four constants occurring in these equations have understandable physical meanings. Two constants determine the logarithmic degree of attenuation, whereas the two others are characteristic epicentral distances. The model can be easily extended to asymmetrical macroseismic fields by introducing an additional parameter, which is a function of azimuth, and can also be a function of the epicentral distance. In the case of an elliptical field this parameter can be expressed analytically. One extra advantage of the presented model's equations is that they are dimensionless. An illustration of the use of the model is given for the region of Slovenia (Yugoslavia).

Kratka vsebina

Na podlagi izbranih kart izoseist preteklih potresov na ozemlju Slovenije dobimo za opisno potresno stopnjo I (uporabljena je potresna lestvica MSK-78) in makroseizmičen pospešek tal a enostaven atenuacijski model, ki ga določa sistem treh linearnih enačb tipa I = f (log r) oz. log a = f (log r), kjer je r epicentralna razdalja (ta je lahko razdalja od epicentra do izoseiste v katerikoli smeri, polmer kroga, ki ima enako ploščino kot območje znotraj izoseiste, v splošnem pa je to razdalja od epicentra do poljubnega mesta). Štiri konstante, ki nastopajo v teh enačbah, imajo razumljiv fizikalen pomen. Dve konstanti določata logaritemsko stopnjo atenuacije, dve pa sta značilni epicentralni razdalji. Model lahko enostavno razširimo na asimetrična makroseizmična polja tako, da vpeljemo dodaten parameter, ki je funkcija azimuta, lahko pa je tudi funkcija epicentralne razdalje. V primeru eliptičnega polja lahko izrazimo ta parameter analitično. Koristna značilnost predloženih modelnih enačb je tudi njihova brezdimenzijska oblika. Ilustracija uporabe modela je dana za znani ljubljanski potres iz leta 1895.

Introduction

In recent years an ever-increasing number of strong-motion records have become available for the analysis of seismic hazard. However, in spite of the vague nature of intensity data, attenuation equations derived from seismic intensity and isoseismal maps, are still very useful, and sometimes the only practical solution to hazard estimation.

Sponheuer (1960) conducted an exhaustive survey of macroseismic methods for determining focal depths, which were directly dependent on attenuation relationships. A more recent extensive survey of commonly used attenuation equations was given by Campbell (1985). In the latter work, the emphasis is on strong-motion attenuation relations, and a brief survey of semi-empirical methods with the prediction of ground motion from intensity is also given.

Howell and Schultz (1975) brought together various proposed attenuation relations into two generalized equations, the more well-known of which is:

$$I_0 - I = a_1 \log r + a_2 r - a_3 \tag{1}$$

where I_0 is the epicentral intensity, and r is the hypocentral distance to the intensity I isoseismal. This equation includes the well-known formula of Kövesligethy, Jánosi and Gassman (Blake, 1941). In equation (1), outside the near-field region some authors (e. g. Gupta & Nuttli, 1976, for $r \geq 20$ km) use the epicentral isoseismal distance for r instead of the hypocentral distance.

Here the use of a particular case of equation (1), when $a_2 = 0$, is analysed, r being the epicentral distance.

Attenuation model for intensity

Circular symmetric macroseismic fields

In order to define the attenuation model, the analysis is based on some marcroseismic data for the territory of Slovenia. In Fig. 1 the territory of Slovenia is presented, marked with the macroseismic field of the strong earthquake which hit Ljubljana on April 14th, 1895. The average attenuation of intensity with epicentral distance is shown, for this earthquake and five others, in Fig. 2. For each earthquake three straight lines have been drawn through the point values of the average distances of isoseismals from the epicentre. In this way the attenuation relation I(log r) has been defined by a group of three linear equations of the type:

$$I_0 - I = b \log r - c \tag{2}$$

where r is the average epicentral distance of the isoseismal I. Average epicentral distance is determined here as a radius of a circle of equivalent area. The coefficients c can be replaced by the characteristic epicentral distances r_0 and r_1, which determine the intersections of the straight lines (Fig 3).

The system of three linear equations which describes the attenuation relation I(log r), is:

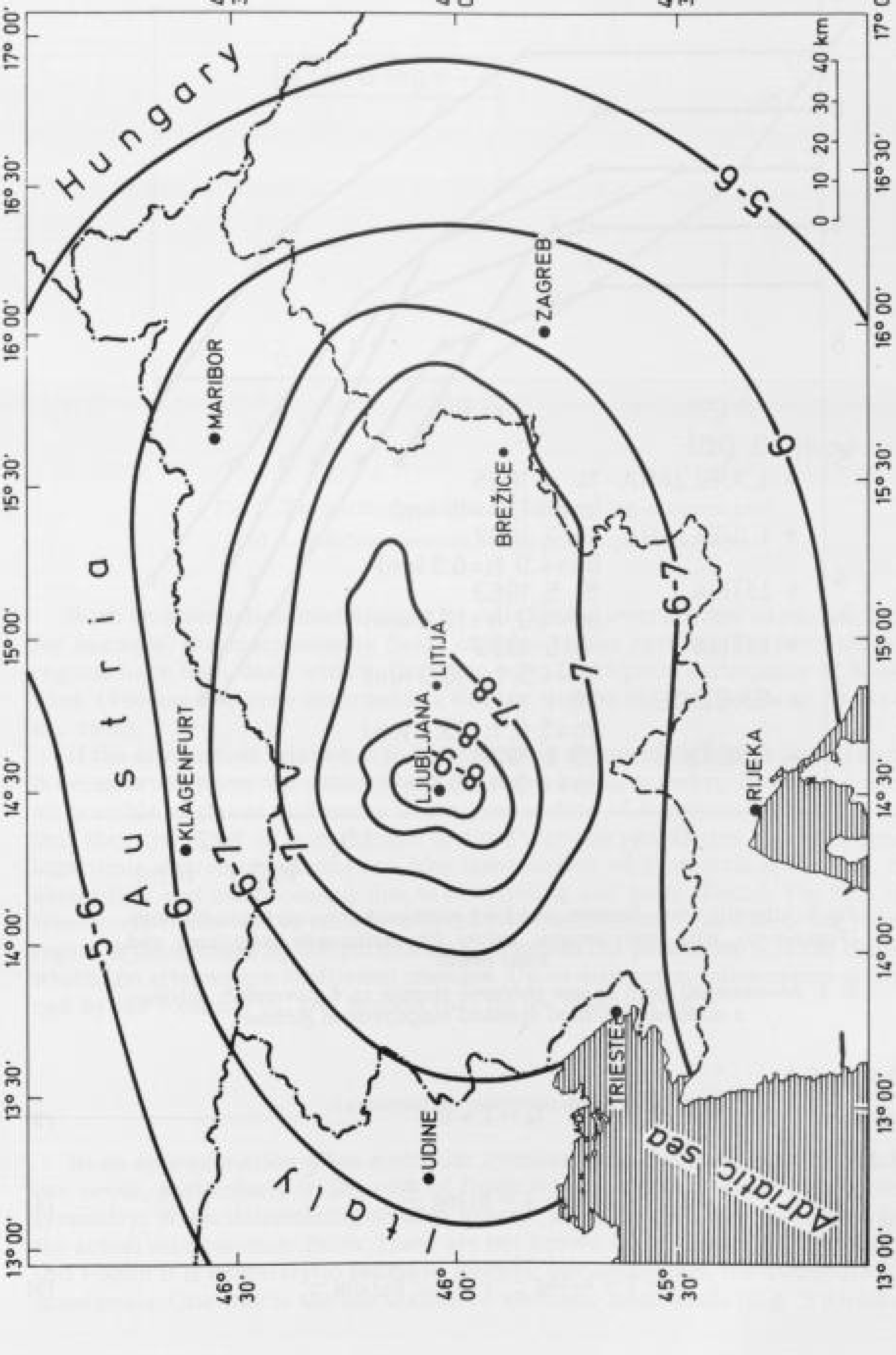

Fig. 1. Isoseismal map relating to the Ljubljana (Slovenia, Yugoslavia) earthquake of April 14th, 1895; I_0 = VIII–IX MSK, m = 6.1, h = 16 km (macroseismic determinations)

Sl. 1. Makroseizmično polje potresa v Ljubljani dne 14. 4. 1895; I_0 = VIII–IX MSK, m = 6.1, h = 16 km (makroseizmične ocene)

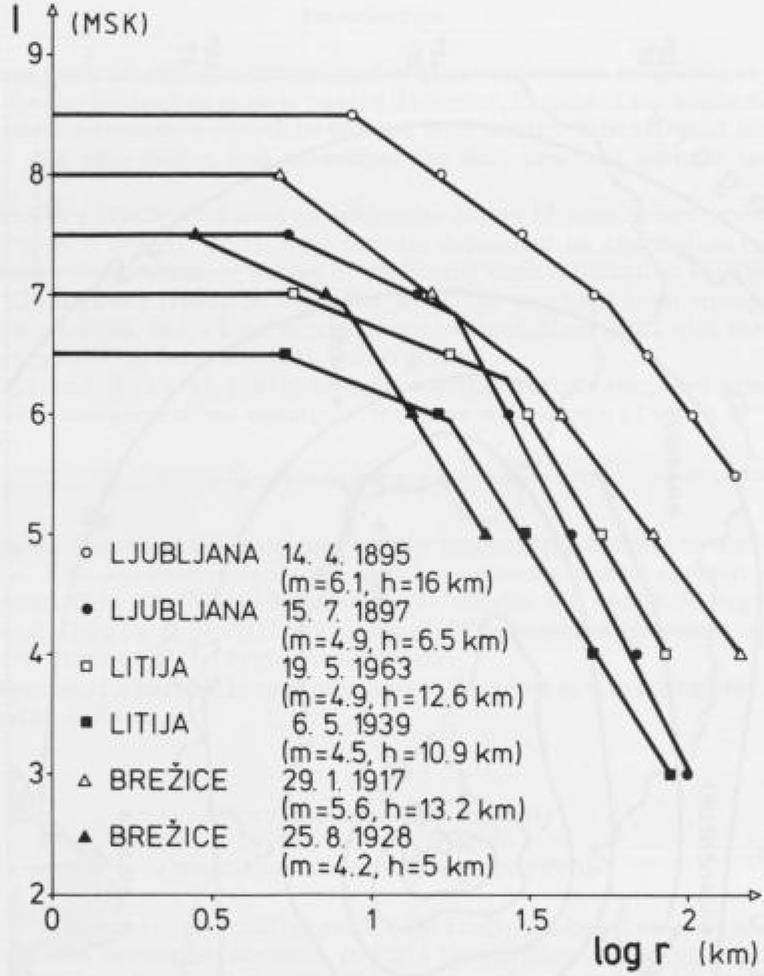

Fig. 2. Intensity – log-distance plot for 6 earthquakes occurring in Slovenia (Yugoslavia), with macroseismic values for earthquake magnitude and focal depth

Sl. 2. Atenuacijski grafi opisne potresne stopnje za 6 slovenskih potresov z makroseizmičnimi ocenami magnitude in globine

for $0 \leq \frac{r}{r_0} \leq 1$:

$$I_0 - I = 0 \tag{3}$$

for $1 \leq \frac{r}{r_0} \leq \frac{r_1}{r_0}$:

$$I_0 - I = b_1 \log \frac{r}{r_0} \tag{4}$$

for $\frac{r}{r_0} \geq \frac{r_1}{r_0}$:

$$I_0 - I = b_2 \log \frac{r}{r_0} - (b_2 - b_1) \log \frac{r_1}{r_0} \tag{5}$$

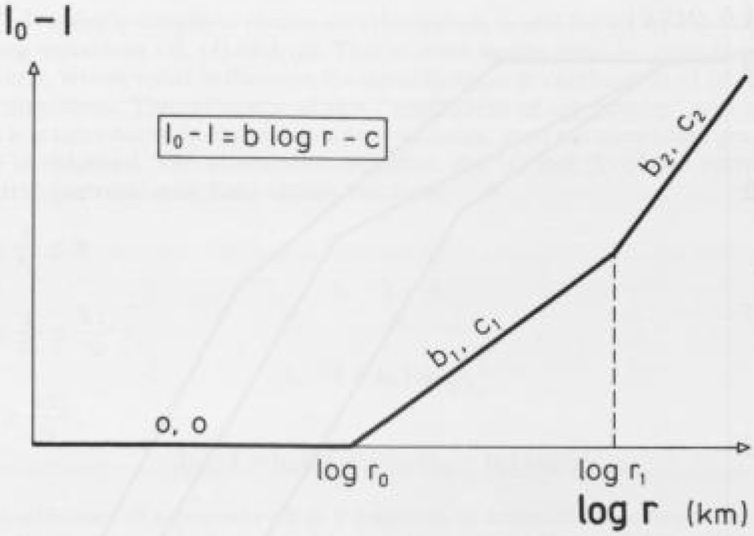

Fig. 3. The parameters of an intensity – log-distance plot

Sl. 3. Količine atenuacijskega grafa opisne stopnje

Such an attenuation model might be suitable for several other cases, too. In Fig. 4, for example, the macroseismic fields of three severe earthquakes from three other regions have been dealt with in the same way. The Irpinia earthquake of November 23rd, 1980 has also been analysed in a similar, though not identical way (Bottari et al., 1986).

If the attenuation relation is to be defined by means of equations (3), (4) and (5), it is necessary to know the values of the constants b_1, b_2, r_0 and r_1. If we put on one side all possible mistakes and errors in the preparation of isoseismal maps, and assume that they are based on fairly objective data, then the parameters b_1 and b_2 represent logaritmic degree of attenuation (the combination of geometric spreading, rate of absorption and enhancement due to channeling and path effects). For this reason, these coefficients will be called "attenuation coefficients". The size of the epicentral region is determined by the parameter r_0, whereas the parameter r_1 is the distance at which the attenuation coefficient changes. Up to distance r_1, attenuation is determined by the constant b_1, and beyond that by the constant b_2.

Asymmetric macroseismic field

In an approximation when a circular symmetric field is used, considerable errors can occur, particularly in the case of fields which vary considerably from circular symmetry. When determining seismic hazard, it would be best to take into account the actual macroseismic fields. These are not known for all possible earthquakes. For this reason it is necessary to estimate, more or less accurately, the distribution of the isoseismals. One way is the calculation of synthetic isoseismals (e. g. Suhadolc et

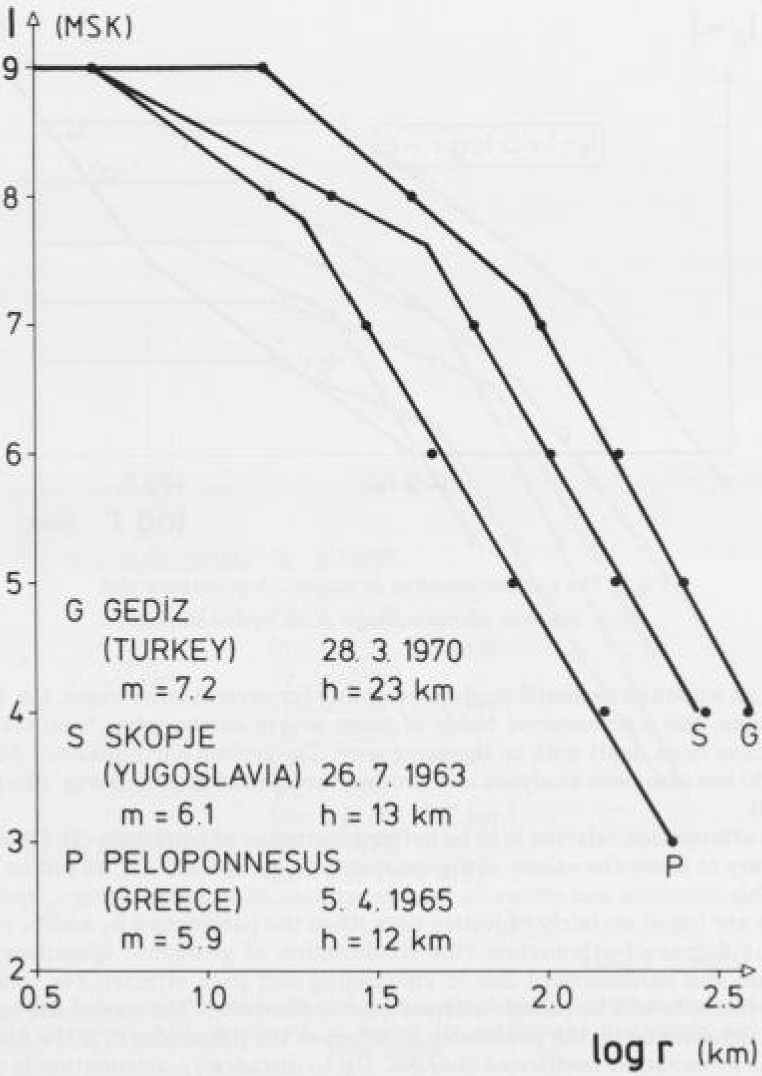

Fig. 4. Intensity – log-distance plot for the Gediz (Turkey) earthquake of March 28th, 1970, for the Skopje (Yugoslavia) earthquake of July 26th, 1963, and for the Peloponnesus (Greece) earthquake of April 5th, 1965, with macroseismically determined magnitudes and depths

Sl. 4. Atenuacijski grafi opisne potresne stopnje za potres v Gedizu (Turčija) dne 28. 3. 1970, za potres v Skopju dne 26. 7. 1963 in za potres na Peloponezu dne 5. 4. 1965 al., 1987). It is fairly simple to obtain an attenuation model for an asymmetric field by expanding equations (3), (4) and (5). This is most easily done by introducing a new parameter k, whose value influences the densification or rarification of isoseismals in various directions. The influence of this "coefficient of asymmetry" can be seen in Fig. 5. If k is introduced in the independent variable, then the simplified graph shown in Fig. 6 is obtained. The attenuation equation (3), (4) and (5) of the corresponding asymmetric macroseismic field obtain the form:

for $0 \le \frac{r}{r_0} \le k$:

$$I_0 - I = 0 \tag{6}$$

for $k \le \frac{r}{r_0} \le \frac{k r_1}{r_0}$:

$$I_0 - I = b_1 \log \frac{r}{k r_0} \tag{7}$$

for $\frac{r}{r_0} \ge \frac{k r_1}{r_0}$:

$$I_0 - I = b_2 \log \frac{r}{k r_0} - (b_2 - b_1) \log \frac{r_1}{r_0} \tag{8}$$

The coefficient of asymmetry k is a function of azimuth. This dependance can be analytically fairly simply expressed in the case of an elliptic field, which is a good approximation for many practical cases. In Fig. 7 the basic quantities of an elliptical field are shown, assuming that the epicentre is on the major axis of the ellipse, between the centre and the focus. For such a field, the coefficient of asymmetry is given by the equation:

$$k = (1 - \varepsilon^2)^{1/4} \frac{\delta(1 - \varepsilon^2)^{1/2} \cos\Theta + (1 - \varepsilon^2 \cos^2\Theta - \delta^2 \sin\Theta)^{1/2}}{1 - \varepsilon^2 \cos^2\Theta} \tag{9}$$

where Θ is the angle between the major axis and the direction in which we are interested in the attenuation, $\varepsilon = c_e/a_e$ is the eccentricity of the elipse, and $\delta = d/a_e$ determines the distance of the epicentre from the centre of the ellipse. If the epicentre is either at the centre of the ellipse ($\delta = O$) or at the focus ($\delta = \varepsilon$), then equation (9) becomes very much simplified.

The model of an asymmetric macroseismic field, as defined in Figs. 5 and 6 and by equations (6), (7) and (8), can if necessary be expanded, e. g. by allowing the attenuation coefficients b_1 and b_2 to be functions of azimuth. This is easily done by introducing two new parameters k_1 and k_2, whose meaning can be seen in Fig. 8. In the case of such an expanded model, the attenuation equations obtain the form:

for $0 \le \frac{r}{r_0} \le k$:

$$I_0 - I = 0 \tag{10}$$

for $k \le \frac{r}{r_0} \le k \left(\frac{r_1}{r_0}\right)^{1/k_1}$:

$$I_0 - I = k_1 b_1 \log \frac{r}{k r_0} \tag{11}$$

for $\frac{r}{r_0} \ge k \left(\frac{r_1}{r_0}\right)^{1/k_1}$:

$$I_0 - I = k_2 b_2 \log \frac{r}{k r_0} - (k_2 b_2 - k_1 b_1) \log \frac{r_1}{r_0} \tag{12}$$

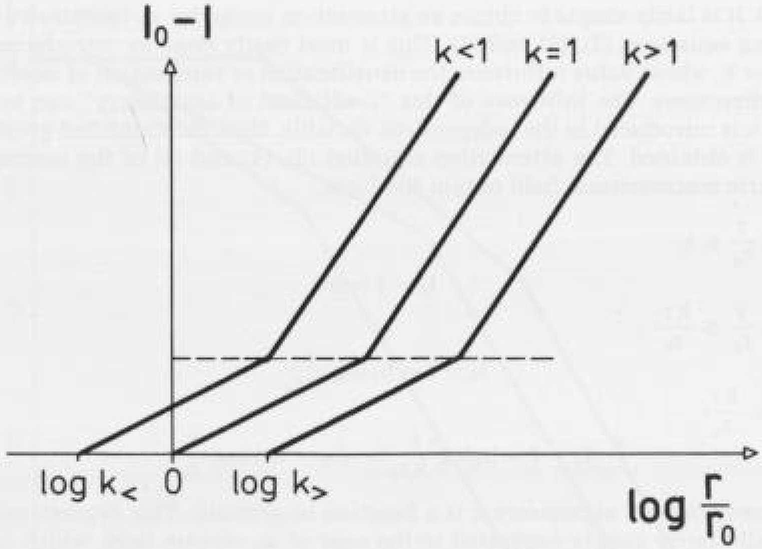

Fig. 5. Intensity – log-distance plot for an asymmetrical macroseismic field; the influence of values of the parameter k on the attenuation curves

Sl. 5. Atenuacijski grafi za nesimetrično makroseizmično polje; vpliv parametra k na mesto grafa

Fig. 6. A simplified intensity – log-distance plot for an asymmetric field

Sl. 6. Skupen atenuacijski graf za nesimetrično makroseizmično polje

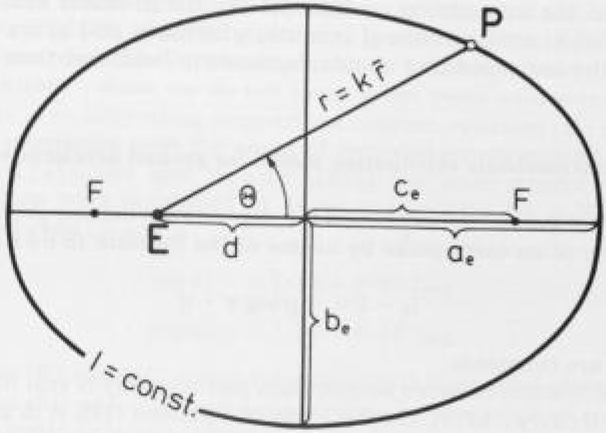

Fig. 7. The parameters of an elliptic macroseismic field. E is the epicenter, F is the focus, and r is the radius of a circle having the same surface area as the ellipse

Sl. 7. Količine eliptičnega makroseizmičnega polja. E je epicenter, F je gorišče, r pa polmer kroga, ki ima enako ploščino kot elipsa

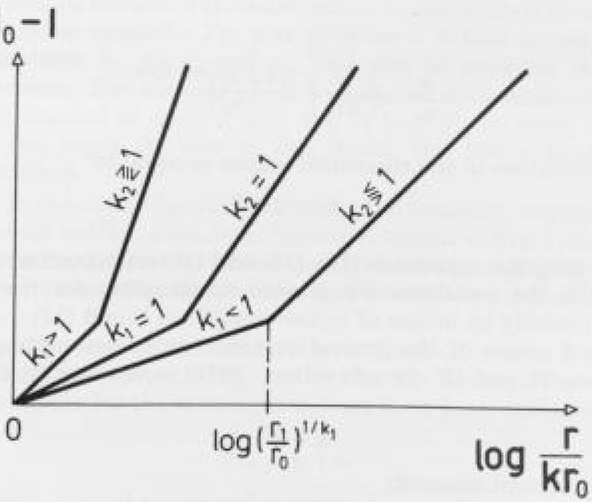

Fig. 8. Intensity – log-distance plot for an asymmetric macroseismic field, showing the influence of parameters k_1 and k_2 on the attenuation curves

Sl. 8. Atenuacijski grafi za nesimetrično makroseizmično polje; vpliv parametrov k_1 in k_2 na obliko grafa

In this model the attenuation coefficients are the products k_1b_1 and k_2b_2. The parameters k_1 and k_2 are functions of azimuth, whereas b_1 and b_2 are the attenuation coefficients of the corresponding circular symmetric field, and thus independent of azimuth.

Macroseismic attenuation model for ground acceleration

In 1906, Kövesligethy first expressed the dependance betwen ground acceleration and the intensity of an earthquake by means of the formula (Sponheuer, 1960):

$$I_0 - I = -p\log a + q \tag{13}$$

where p and q are constants.

This form of relation between acceleration and intensity is still in use today (e. g. Trifunac & Brady, 1975). On the basis of equation (13), it is possible to write down the attenuation model for ground acceleration, which is expressed for intensity in equations (6), (7) and (8), as follows:

for $0 \le \frac{r}{r_0} \le k$:

$$\frac{a}{a_0} = 1 \tag{14}$$

for $k \le \frac{r}{r_0} \le k\frac{r^1}{r_0}$:

$$\frac{a}{a_0} = \left(\frac{r}{k r_0}\right)^{-b_1/p} \tag{15}$$

for $\frac{r}{r_0} \ge k\frac{r^1}{r_0}$:

$$\frac{a}{a_0} = \left(\frac{r}{k r_0}\right)^{-b_2/p}\left(\frac{r_1}{r_0}\right)^{(b_2 - b_1)/p} \tag{16}$$

Ground acceleration in the epicentral region is equal to:

$$a_0 = 10^{q/p} \tag{17}$$

In the same way that equations (14), (15) and (16) have been written, it would be possible to write the equations for ground acceleration for the model which is expressed for intensity by means of equations (10), (11) and (12).

For tabulated values of the ground acceleration corresponding to the MSK-78 intensity betwen VI and IX (Medvedev, 1978) equation (13) has the following form:

$$a = 2^{I-7} \tag{18}$$

(a in metres per second squared).

The values of the coefficients p and q are obtained from equations (13) and (18):

$$p = \frac{1}{\log 2} \tag{19}$$

$$q = I_0 - 7 \tag{20}$$

The attenuation model defined by equations (14), (15) and (16) should, with the use of equations (18), (19) and (20), give "peak ground accelerations". In order to be precise, these macroseismically obtained values will be instead called "MSK-78 ground accelerations", since we do not know what these values really are. In this connection there is an interesting comparison between equation (18) and the correlation of seismic intensities with the peaks of recorded strong ground motion, as was carried out by Trifunac and Brady (1975). For peak ground acceleration the following relations were obtanined by these two authors for a Modified Mercalli intensity I_{MM} between IV and X:

$$\log a_V = -2 \cdot 18 + 0 \cdot 30\, I_{MM} \tag{21}$$

$$\log a_H = -1 \cdot 99 + 0 \cdot 30\, I_{MM} \tag{22}$$

where subscripts "V" and "H" designate vertical and horizontal components, respectively. Equations (21) and (22) have been written here in units of metre per second squared. Let us write equation (18) in the same form:

$$\log a_{MSK-78} = -2 \cdot 11 + 0 \cdot 30\, I_{MSK-78} \tag{23}$$

The values of a_{MSK-78} are somewhere between the values of a_V and a_H, which are determined by equations (21) and (22) for MM intensity. The values of a_H are approximately 30 % greater than the values of a_{MSK-78}, whereas these are about 20 % greater than a_V.

Illustration of use of the model

Let us take a look at the use of the attenuation model defined by equations (6), (7) and (8), on a practical example. For this purpose it is first necessary to estimate values of the constants b_1, b_2, r_o and r_1. This will be done for the seismological conditions in Slovenia. The starting-point will be the data shown in Figs. 1 and 2. Due to the small amount of data, it will not be possible to carry out a statistical evaluation, this not being the aim of this paper, but just a rough estimate for illustrating the method.

With respect to similarity between individual attenuation curves, the macroseismic fields of the six earthquakes from Slovenia, shown in Fig. 2, can be separated into two groups: earthquakes with a focal depth of $h < 13$ km (Fig. 9), and those with a focal depth of $h > 13$ km (Fig. 10). For the first group $b_1 \approx 1.1$ and $b_2 \approx 4.6$, and for the second group $b_1 \approx 2.0$ and $b_2 \approx 3.5$.

From the data about the (macroseismically determined) depths h and magnitudes m, as well as about the values of r_0 and r_1 for the earthquakes concerned, the following two equations for the least square lines have been obtained:

$$2 r_0 = 1 \cdot 1\, h \tag{24}$$

$$m = 2 + 5 \log \frac{r_1}{r_0} \tag{25}$$

The relations are shown graphically in Figs. 11 and 12. From equations (24) and (25) we obtain:

$$r_1 = h\, 10^{(m - 3 \cdot 3)/5} \tag{26}$$

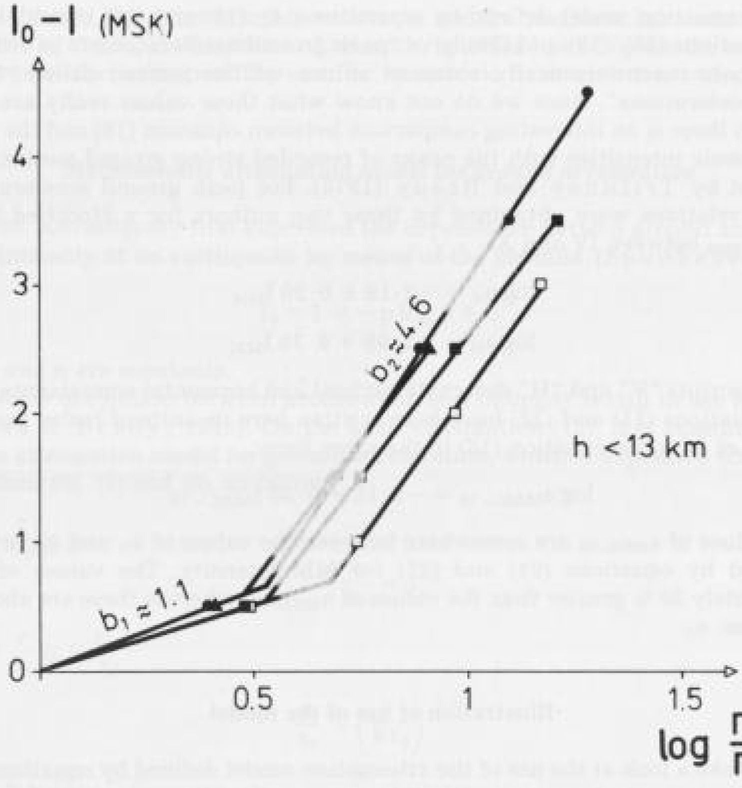

Fig. 9. Intensity – log-distance plot for earthquakes occurring in Slovenia (Yugoslavia), with a focal depth of $h < 13$ km

Sl. 9. Atenuacijski grafi opisne potresne stopnje za 4 slovenske potrese z žariščno globino manjšo od 13 km

On the basis of the above derivations, using equations (6), (7) and (8) the model macroseismic field for the earthquake whose macroseismic field is shown in Fig. 1 will be calculated. Since the depth of this earthquake is 16 km, the attenuation coefficients are $b_1 = 2.0$ and $b_2 = 3.5$. From equations (24) and (26) we then obtain: $r_0 = 8.8$ km and $r_1 = 58.1$ km. In order to determine the coefficients of asymmetry, an approximation using an elliptical field has been assumed, estimating the values of parameters ε and δ from Fig. 1. Due to the changes in the direction of the ellipse, the analysis has been limited to the mean epicentral distances, at which the longer axis is almost in the direction East–West. The eccentricity of the ellipse ε is approximately 0.80, and δ is approximately 0.24.

The result of the calculation is shown in Fig. 13. The middle line, marked $\bar{I}$, defines the average model attenuation curve for the earthquake of 14. 4. 1985, whereas the right-hand line, marked I_{max}, defines the model attenuation curve in the directin of slowest attenuation ($\Theta = 0$, i. e. in the direction East–West), and the left-hand line, marked I_{min}, defines the model attenuation curve in the direction of most rapid attenuation ($\Theta = 104°$ and $\Theta = 256°$). The model curves for all other directions lie

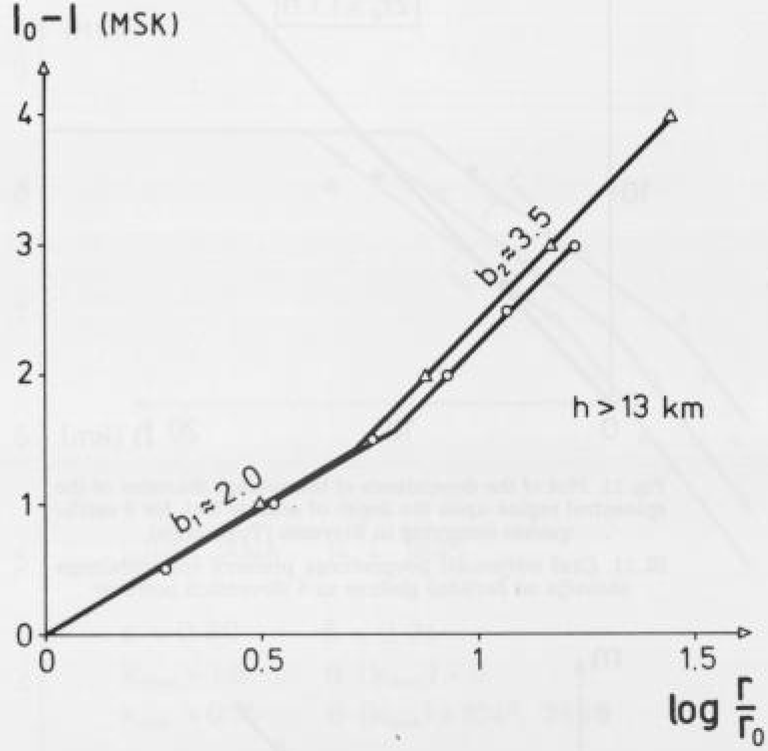

Fig. 10. Intensity – log-distance plot for earthquakes occurring in Slovenia (Yugoslavia), with a focal depth h > 13 km

Sl. 10. Atenuacijska grafa opisne potresne stopnje za 2 slovenska potresa z žariščno globino večjo od 13 km

between the last two mentioned lines. The corresponding attenuation curves for MSK-78 ground acceleration ($\bar{a}$, a_{min} and a_{max}) are shown in Fig. 14. The same relations are shown in a different form in Fig. 15, where the attenuation curve proposed by Drakopoulos and Makropoulos (1987), marked D&M, has been drawn in. The latter authors have, for the Balkan area, proposed the following attenuation equation for peak ground acceleration (written here in units of metre per second squared):

$$a = 3\cdot 22\, e^{0\cdot 69\, m}(r + 10)^{-1\cdot 37} \tag{27}$$

where r is the focal distance in kilometres. In Figs. 13, 14 and 15 the actual values determined from Fig. 1 are given in addition to the model attenuation curves.

Espinosa (1980) has also defined the depedence of log a on log r for a circular symmetric field by means of a system of three linear equations. If we use his attenuation equations for the case being studied here (they are actually valid for the western United States), then it turns out that in the case of small epicentral distances they provide larger values, and in the case of large epicentral distances significantly smaller values then those given by our model in the case of a circular symmetric field.

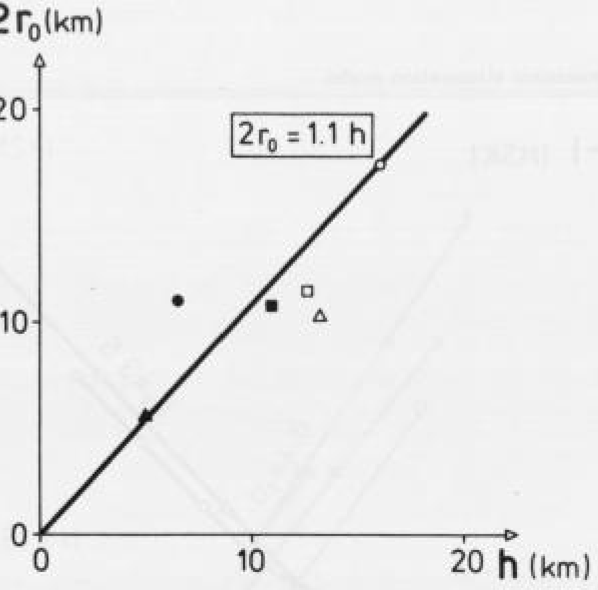

Fig. 11. Plot of the dependence of the average diameter of the epicentral region upon the depth of seismic foci, for 6 earthquakes occurring in Slovenia (Yugoslavia)

Sl. 11. Graf odvisnosti povprečnega premera epicentralnega območja od žariščne globine za 6 slovenskih potresov

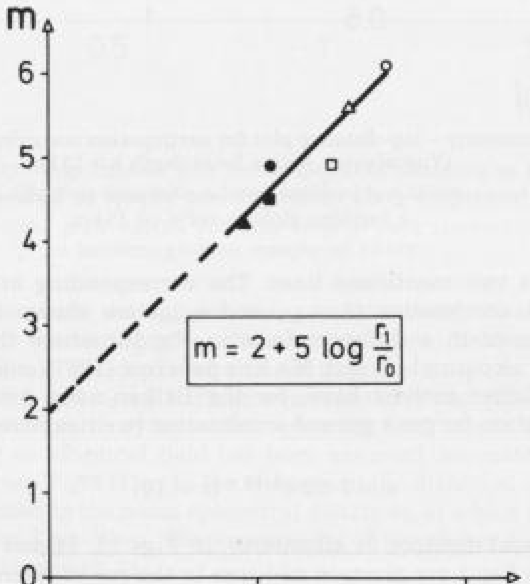

Fig. 12. Plot of the dependance of macroseismic magnitude upon the logarithem of the ratio r_1/r_0, for 6 earthquakes occurring in Slovenia (Yugoslavia)

Sl. 12. Graf odvisnosti makroseizmične magnitude od logaritma razmerja r_1/r_0 za 6 slovenskih potresov

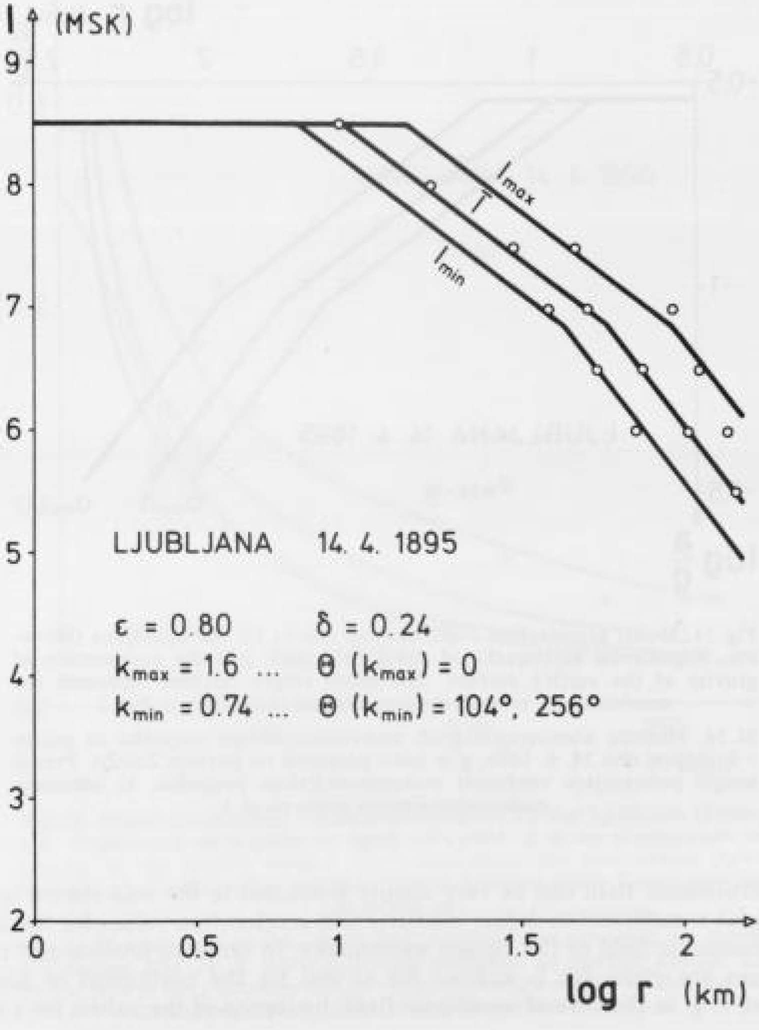

Fig. 13. Model intensity – attenuation curves for the Ljubljana (Slovenia, Yugoslavia) earthquake of April 14th, 1895; the small empty circules represent the intensities, which are taken from the isoseismal map of Fig. 1

Sl. 13. Modelni atenuacijski grafi opisne potresne stopnje za potres v Ljubljani dne 14. 4. 1895; prazni krogci ponazarjajo vrednosti, ki ustrezajo makroseizmičnemu polju na sl. 1

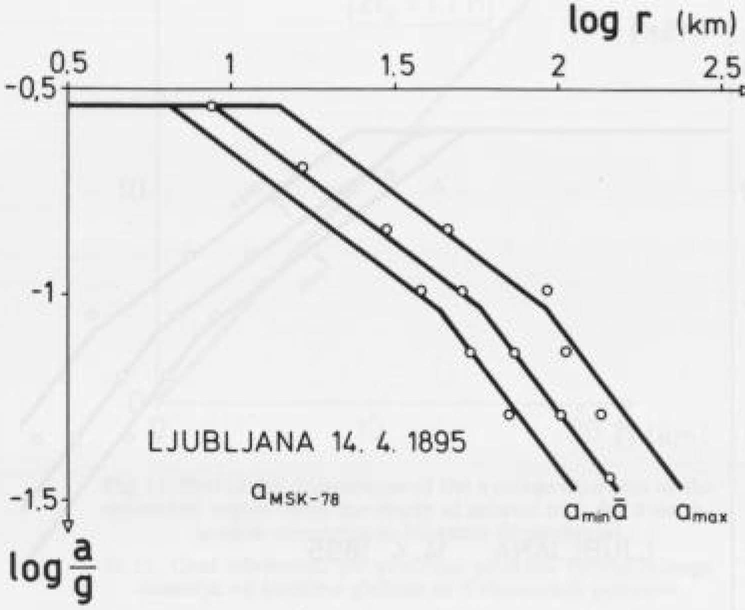

Fig. 14. Model acceleration – attenuation curves for the Ljubljana (Slovenia, Yugoslavia) earthquake of April 14th, 1895; g is the acceleration of gravity at the earth's surface. The small empty circules represent the accelerations, which corespond to the intensities in Fig. 1

Sl. 14. Modelni atenuacijski grafi makroseizmičnega pospeška za potres v Ljubljani dne 14. 4. 1895; g je težni pospešek na površju Zemlje. Prazni krogci ponazarjajo vrednosti makroseizmičnega pospeška, ki ustrezajo makroseizmičnemu polju na sl. 1

A macroseismic field can be very simply presented in the way shown in Fig. 16. Just one plot is sufficient to define intensity and acceleration values for the asymmetric macroseismic field of the chosen earthquake. In order to provide full information, values are given for I_0 and a_0, for r_0 and for the coefficient of asymmetry k (defined, e. g. in the case of an elliptic field, by means of the values for ε and δ).

Discussion

Although the proposed attenuation model has been verified on only a small number of macroseismic fields, its applicability appears to be fairly widespread. This is indicated by the examples in Fig. 4, and several other similar examples from the literature (e. g. Bottari et al., 1986, and Espinosa, 1980).

For practical purposes we can limit ourselves to the model defined by equations (6), (7) and (8) for intensity, and by equations (14), (15) and (16) for "macroseismic" accelaration. If it is assumed that the coefficient of asymmetry changes with epicentral distance (e. g. in sections), then it is possible to deal with macroseismic fields of various kinds.

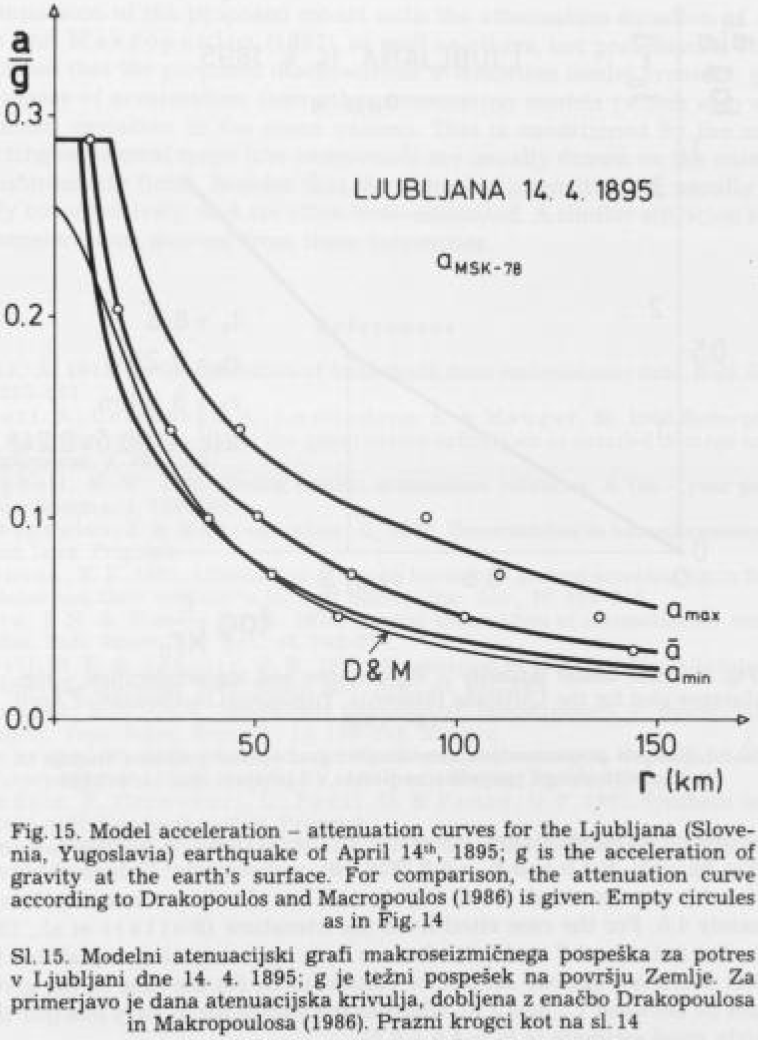

Fig. 15. Model acceleration – attenuation curves for the Ljubljana (Slovenia, Yugoslavia) earthquake of April 14th, 1895; g is the acceleration of gravity at the earth's surface. For comparison, the attenuation curve according to Drakopoulos and Macropoulos (1986) is given. Empty circules as in Fig. 14

Sl. 15. Modelni atenuacijski grafi makroseizmičnega pospeška za potres v Ljubljani dne 14. 4. 1895; g je težni pospešek na površju Zemlje. Za primerjavo je dana atenuacijska krivulja, dobljena z enačbo Drakopoulosa in Makropoulosa (1986). Prazni krogci kot na sl. 14

The strength of the model is in its simplicity (to which the dimensionless form of the equations contributes, though not essentially) and possibly in the simple relations between the parameters b_1, b_2, r_0, r_1 and k, on the one hand, and the geological structure and focal parameters, on the other. The extent to which the model can be used depends on how-defined these parameters are. Together with the coefficient of asymmetry k, the average attenuation coefficients b_1 and b_2 define attenuation at lesser and greater epicentral distances. In the model, for the epicentral region, i. e. up to a distance of r_0, a constant value of intensity or acceleration, respectively, is assumed, since usually only one value is available for this area. If a range of values is given, then it is usually assumed that the spread of values is due to changing local geological and geotechnical properties of the ground.

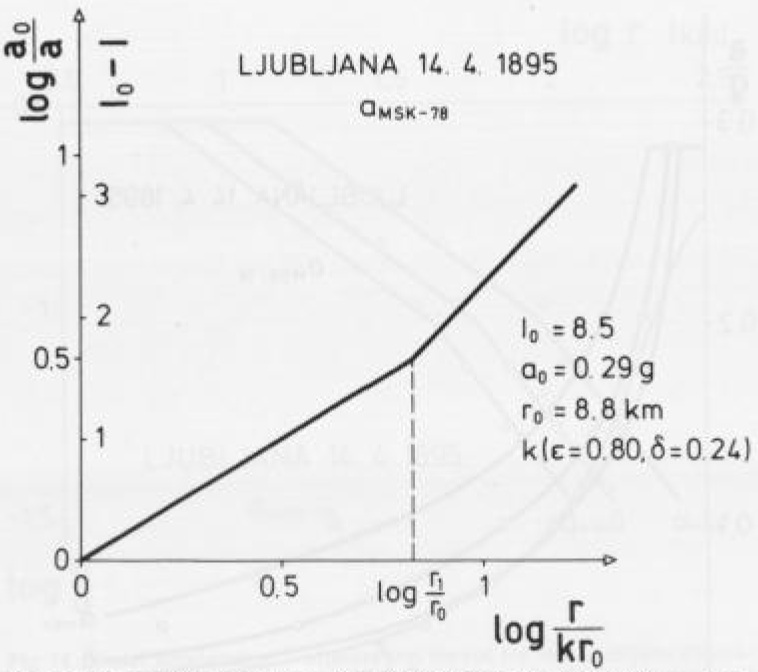

Fig. 16. Joint model intensity – log-distance and log-acceleration – log-distance plot for the Ljubljana (Slovenia, Yugoslavia) earthquake of April 14th, 1895

Sl. 16. Skupen poenostavljen atenuacijski graf opisne potresne stopnje in makroseizmičnega pospeška za potres v Ljubljani dne 14. 4. 1895

For the described earthquakes, occurring in the territory of Slovenia, $b_1 \approx 1.1$ and $b_2 \approx 4.6$ (Fig. 9), or $b_1 \approx 2.0$ and $b_2 \approx 3.5$ (Fig. 10), respectively. Values of between 1.4 and 2.3 for b_1 can be read from Fig. 4, and in all three cases b_2 is equal to approximately 4.5. For the case cited from the literature (Bottari et al., 1986), the value of b_1 lies between 1.7 and 2.0, whereas b_2 is approximately equal to 4.0. It can be seen that there is a greater scatter of values for b_1 (in the case of the given data, these values lie between 1.1 and 2.3), whereas the values for b_2 vary less (for the given data, a fairly good estimate is $b_2 = 4.0 + 0.5$).

It appears that the parameter b_1, and thus attenuation to a distance r_1, is considerably dependent on local seismo-geological conditions, whereas the average attenuation from a distance r_1 onwards is fairly similar in the case of earthquakes from different regions, as the studied macroseismic fields have indicated. It should also be remembered that errors in determining b_1 are considerably greater than those in determining b_2.

How well the parameter r_0 is defined depends upon the determination of the epicentral region, whose size, as a rule, increases with increasing focal depth and magnitude. In the cases dealt with here, the parameter r_1 shows even greater dependence on these two seismic parameters. Equations (24), (25) and (26) must be considered as just a temporary aid for determining values of r_0 and r_1, since they have been derived from a relatively small amount of data.

A comparsion of the proposed model with the attenuation equation of Drakopoulos and Makropoulos (1987), as well as others, not presented in this paper, has indicated that the proposed macroseismic attenuation model provides, generally, greater values of acceleration than other attenuation models (which also often add one standard deviation to the mean values). This is conditioned by the method of constructing isoseismal maps (the isoseismals are usually drawn on the outer margin of each isointensity field). Besides that the values of intensities are usually determined fairly conservatively, and are often over-estimated. A similar situation holds true for the accelerations derived from these intensities.

References

Blake, A. 1941, On the estimation of focal depth from macroseismic data. Bull. Seism. Soc. Am., *31*, 225–231.

Bottari, A., Corsanego, A., Lo Giudice, E. & Mauger, M. 1986, Some problems in the MSK scale applications: Use of the quantitative definitions in detailed damage assessment. Ann. Geophysicae, *4*, 191–199.

Campbell, K. W. 1985, Strong motion attenuation relations: A ten – year perspective. Earthquake Spectra, *1*, 759–804.

Drakopoulos, J. & Makropoulos, C. 1987, Uncertainties in hazard assessment due to attenuation laws. Preprint.

Espinosa, E. F. 1980, Attenuation of strong horizontal ground acceleration in the western United States and their relation to M. Bull. Seism. Soc. Am., *70*, 583–616.

Gupta, I. N. & Nuttli, O. W. 1976, Spatial attenuation of intensities for central U. S. earthquakes. Bull. Seism. Soc. Am., *66*, 743–751.

Howell, B. F. & Schultz, T. R. 1975, Attenuation of Modified Mercalli intensity with distance from the epicenter. Bull. Seism. Soc. Am., *65*, 651–665.

Medvedev, S. V., 1978, Opredelenie intensivnosti zemletrjasenij. V: Epicentralnaja zona zemletrjasenij. Vopr. Inžen. Sejsmol., *19*, 108–116, Moskva.

Sponheuer, W. 1960, Methoden zur Herdtiefenbestimmung in der Makroseismik. Freiberger Forschungshefte, C 88, Geophysik, Akademie Verlag, Berlin, 120 pp.

Suhadolc, P., Cernobori, L., Pazzi, G. & Panza, G. F. 1987, Synthetic isoseismals: Applications to Italian earthquakes. Preprint.

Trifunac, M. D. & Brady, A. G. 1975, On the correlation of seismic intensity scale with the peaks of recorded strong ground motion. Bull. Seism. Soc. Am., *65*, 139–162.