ATTENUATION OF PEAK HORIZONTAL AND VERTICAL ACCELERATION IN THE DINARIDES AREA

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Summary: Peak acceleration attenuation relations for horizontal and vertical components are presented for the Dinarides region, based on 145 3-component accelerograms related to 46 earthquakes with local magnitudes of 4.5 or greater and with epicentral distances of less than 200 km as recorded on 39 recording sites in the greater Dinarides region. The attenuation functions were obtained by two-stage stratified regression on the local magnitude and epicentral distance as independent variables. The predicted peak acceleration values within the distance range covered by the data are comparable to the ones obtained for stiff-soil or rock sites when selected reference relations are used. The rather large average residuals are caused mostly by the lack of information on local site conditions and by the use of epicentral distance instead of fault distance.

Keywords: strong ground motion, peak acceleration, attenuation, Dinarides, Croatia

1. INTRODUCTION

Although the expected peak acceleration is still one of the most often used parameters in earthquake resistant design of engineering structures, no published attenuation relationship is available for the Dinarides region, which includes the seismically most active part of Croatian territory. The earthquakes occur there as a result of collision and interaction of the Adriatic platform and the Dinarides. In practice, for the purposes of engineering seismology related studies in Croatia, either relations derived for other regions are used – most often those by Joyner and Boore (1981) for California, Boore et al. (1997) for western North America, Sabetta and Pugliese (1987, 1996) for Italy, and Ambraseys et al. (1996) for Europe – or relations published only in in-house reports and other specialized studies are applied (e.g., relation GZ300 by Prelogović et al., 1995). The purpose of this study is to derive appropriate attenuation relations to be used in the Dinarides region based on all available strong-motion data.

2. THE DATA

The data set at our disposal consists of 295 3-component accelerograms recorded by the SMA-1 Kinematics type accelerographs in the region in the period 1973 – 1996. The records were obtained at 42 sites and generated by 155 earthquakes ranging in local magnitude (Ml) from 2.6 to 6.8. The distance range covered is 1 – 340 km. Due to the poor reliability of SMA-1 records for small-magnitude earthquakes, and to avoid problems related to a possible change of geometrical spreading when surface waves start to dominate over body waves at large distances, for further analyses we only kept data...
related to earthquakes with $M_L \geq 4.5$ obtained at epicentral distances of up to 200 km. With these restrictions applied, there remained 145 3-component accelerograms, originating from 46 earthquakes, which were recorded at 39 sites. The map of epicentres and stations is shown in Fig. 1. Fig. 2 presents the magnitude-distance distribution of the data set. The data up to 1983 were adopted from Jordanovski et al. (1987), taking addenda and corrections of Herak et al. (1987) into account. The accelerograms were digitized, band-pass filtered and corrected in the standard way (see Jordanovski et al., 1987 for details). The band-pass frequencies correspond to the frequency band within which the signal-to-noise ratio is greater than one, the widest possible band being 0.07 – 25 Hz. Records after 1983 are taken from the archives of digitized accelerograms of the Geophysical Institute in Zagreb. All accelerograms were recorded on instruments installed on the ground floor or in the basements of relatively small structures. At present, information on local soil properties is available for only a small portion of the recording sites and has, therefore, not been considered. Based on the knowledge of the regional geological setting, an educated assumption that most of the sites may be classified as "rock" or "stiff soil" is probably correct.
3. RESULTS

The attenuation of peak acceleration is modelled using local magnitude ($M_L$) and epicentral distance ($D$) as independent variables. We were unable to use the closest distance to the surface fault-projection ($R$) (Joyner and Boore, 1981), which is preferred over the epicentral distance, because the data on the causative fault geometry are of insufficient accuracy for the majority of events considered. The type of the attenuation relation considered is:

$$\log a_{\text{max}} = c_1 + c_2 M_L + c_3 \log \sqrt{c_4^2 + D^2}$$

Here $a_{\text{max}}$ is the larger peak absolute acceleration in the two horizontal components, or the peak absolute vertical acceleration, expressed in units of $g$. Form (1) is used, e.g., by Ambraseys et al. (1996). It was also used by Sabetta and Pugliese (1987), but with $c_3$ fixed as $c_3 = 1$. Sometimes an additional distance-proportional term which takes anelastic attenuation into account is also considered. Our data set was found to be inadequate for an independent determination of geometrical and inelastic attenuation effects, so this term was ignored.

Inspection of Fig. 2 reveals that there is a correlation between magnitude and distance, which may induce bias between the magnitude ($c_2$) and distance ($c_3$) coefficients in (1). In an attempt to decouple these two terms, we performed a two-stage stratified regression, similar to the one proposed by Joyner and Boore (1981) (see also, e.g., Fukushima and Tanaka, 1990). However, because there are many earthquakes with only a few records in our data set, instead of grouping together the data belonging to the same earthquake, the
Table 1. Regression coefficients in Eq. (1) and their standard errors.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Horizontal component</th>
<th>Vertical component</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_1$</td>
<td>$-1.300 \pm 0.192$</td>
<td>$-1.518 \pm 0.293$</td>
</tr>
<tr>
<td>$c_2$</td>
<td>$0.331 \pm 0.040$</td>
<td>$0.302 \pm 0.035$</td>
</tr>
<tr>
<td>$c_3$</td>
<td>$-1.152 \pm 0.099$</td>
<td>$-1.061 \pm 0.096$</td>
</tr>
<tr>
<td>$c_4$</td>
<td>$11.8 \pm 4.8$</td>
<td>$11.0 \pm 5.5$</td>
</tr>
<tr>
<td>standard error of the fit, $\sigma$</td>
<td>$0.311$</td>
<td>$0.313$</td>
</tr>
</tbody>
</table>

The data have been divided into classes based on the magnitude of the related event. This approach was also tried by Ambraseys et al. (1996). The obtained regression coefficients and their standard errors are presented in Table 1, and the relations read:

$$
\log a_{\text{max,}h} = -1.300 + 0.331 M_L - 1.152 \log \sqrt{D^2 + 11.8^2} + 0.311 P 
$$

(2)

$$
\log a_{\text{max,v}} = -1.518 + 0.302 M_L - 1.061 \log \sqrt{D^2 + 11.0^2} + 0.313 P 
$$

(3)

$P$ in the above expressions is equal to zero for mean values, and to one for 84-percentile values of $\log a_{\text{max}}$. Indices 'h' and 'v' correspond to horizontal and vertical components, respectively. All coefficients were found to be significantly different from zero at levels exceeding 0.999. A direct one-stage nonlinear regression using the Levenberg-Marquardt technique for minimizing the sum of squared residuals produced practically equal regression coefficients with somewhat larger standard errors.

The fit of relations (2) and (3) to the data is illustrated in Fig. 3. The residuals are distributed approximately log-normally (Fig. 4), with slight asymmetry showing longer tails on the positive side in both components. This is most probably caused by site amplification at some stations, and is balanced by a larger than expected number of residuals in the first negative class. Fig. 5 shows that there is no distance dependence of residuals for any of the components, even for large distances. Residuals are also not magnitude-dependent as seen in Fig. 6.

4. DISCUSSION

Figs. 7 and 8 present the comparison of relations (2) and (3) with the most often used empirical attenuation laws in Croatia – the ones published by Sabetta and Pugliese (1987, 1996), Ambraseys (1995), Ambraseys and Simpson (1996), Ambraseys et al. (1996), and Boore et al. (1997). These reference relations will from now on be referred to as SP87, SP96, A95, AS96, ASB96 and BJF97, respectively. In order to make comparisons possible we had to adapt our relations to make them compatible with the reference relations, i.e. to harmonize the usage of magnitude, horizontal distance and the choice of average observed horizontal acceleration vs. larger horizontal component.
Fig. 3. Fit of equations (2) and (3) to the data. Top row: magnitude interval $4.5 \leq M_L < 5.5$, the mean magnitude within the interval is 4.85. Middle row: magnitude interval $5.5 \leq M_L < 6.5$, the mean magnitude within the interval is 5.95. The bottom row shows observations related to the great Montenegro event of 1979 ($M_L = 6.8$). The smallest circles correspond to magnitudes at the lower limit and their increase in size with magnitude. Left: horizontal components; right: vertical components. Short and long dashed lines bound ±1σ and ±2σ intervals, respectively.

In SP87 and SP96 a combination of surface-wave magnitude ($M_S$) and local magnitude ($M_L$) is used, A95, AS96 and ASB96 make use only of $M_S$, BJF97 use the moment magnitude ($M$), whereas here $M_L$ is adopted as reported in the updated Croatian Earthquake Catalogue (Herak et al., 1996). To the best of our knowledge no published relationships between $M_S$ and $M_L$ or between $M$ and $M_L$ exist for the Dinarides area.
Unpublished studies carried out at the Department of Geophysics in Zagreb indicate that $M_L$ as reported in Herak et al. (1996) closely correspond to world-wide estimates of $M_S$. We have, therefore, chosen not to convert our $M_L$ to $M_S$ or $M$ for the purpose of comparisons, which is also in agreement with the findings of Hanks and Kanamori (1979) who consider $M$ to be equivalent to $M_L$ in the range $3 < M_L < 7$, and to $M_S$ in the range $5 < M_L < 7.5$.

All reference relations have been derived considering the fault distance ($R$), i.e. the distance to the surface projection of the ruptured part of the fault plane as defined in Joyner and Boore (1981). In addition, SP87 and SP96 report also expressions using epicentral distance ($D$), which is also used here for the reasons stated above. From the very definition of $R$ it is clear that these two measures are similar for small faults (small magnitudes) and will be, on average, very different ($R \neq D$) close to a causative fault of a major earthquake. It follows that no general conversion $D \leftrightarrow R$ is possible. The curves in Figs. 7 and 8 corresponding to Eqs. (2) and (3) were, therefore, obtained by converting $D$ into the average fault distance ($R_{av}$), which is defined as the average distance of a point on a circle of radius $D$ to the rectangle representing the fault projection to the Earth’s surface, as schematically shown in Fig. 9. The dimensions of the rectangle depend on the magnitude and the fault’s average dip-angle ($\delta$) in the region. In our case we used $L = 60$, $W = 4$ for $M_L = 7$, $L = 15$, $W = 2$ for $M_L = 6$ and $\delta = 75^\circ$, which is consistent with the results of Wells and Coppersmith (1994) and with observations in the Dinarides.

All reference relations except BJF97 were derived using the larger of the two recorded horizontal peak accelerations. As BJF97 use the average observed horizontal acceleration, the values computed by Eqs. (2) and (3) were divided by 1.15, which is the mean ratio between the maximal and the average observed peak acceleration of the two components for our data set.

Inspection of Fig. 7 reveals that peak horizontal accelerations predicted by our Eq. (2) very closely match the ones obtained using BJF97 (top row in Fig. 7) if the average velocity of shear waves in the topmost 30 m of soil ($V_{30}$) in BJF97 is set between 600 and
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1500 m/s, which is characteristic of rock or very stiff soil sites. The middle row of Fig. 7 compares (2) with the ASB96 reference relation. It is seen, that within the range of distances covered by the data the two agree quite well, somewhat better if ASB96 soft-soil category (S) is assumed instead of rock (R). For distances smaller than the minimum distance \(D_{\text{min}}\) (black dots in Figs. 7 and 8) in our data set, ASB96 predict considerably higher \(a_{\text{max,h}}\). Similar behaviour is seen in the bottom two subplots in Fig. 7, which compare Eq. (2) with the SP87 empirical attenuation law. Within the distance range covered by the data in the two data sets, the agreement is rather good, and (2) seems to be more similar to the SP87 rock-site category (R). Extrapolations beyond \(D_{\text{min}}\), however, again yield acceleration values considerably lower than the reference expression.

Fig. 5. Distribution of residuals \((d)\) of \(\log(a_{\text{max,h}})\) (top) and \(\log(a_{\text{max,v}})\) (bottom) with epicentral distance \((D)\). The correlation coefficients between \(\log D\) and horizontal and vertical residuals are equal to \(-0.0026\) and \(-0.0035\), respectively.

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Fig. 6. Distribution of residuals (d) of log($a_{\text{max, h}}$) (top) and log($a_{\text{max, v}}$) (bottom) with local magnitude ($M_L$). The correlation coefficients between $M_L$ and horizontal and vertical residuals are equal to 0.0024 and −0.0003, respectively.

As regards the vertical component, a good correspondence is seen between Eq. (3) and the AS96 relation, even for distances smaller than $D_{\min}$. SP96 also predicts comparable values of $a_{\text{max, v}}$ for $D > D_{\min}$, but significantly diverges from (3) close to the source yielding over 200% larger values in the epicentre for $M_L = 7$ at soil sites than any of the attenuation laws considered.

As a rule, (2) and (3) exhibit a flat part at short distances ($D < 5$ km) that is longer than in most of the cited relations (the only exception is BJF97, especially for large magnitudes) and thus yield values close to the epicentre that are lower than would be predicted by the reference formulas. This is caused by the rather high value of the pseudo-
depth parameter $c_4$, which is 2–3 times higher than in other attenuation laws considered, and is approximately equal to the mean hypocentral depth of 12 km in the Dinarides region (Herak and Herak, 1990).

Fig. 7. Comparison of peak horizontal accelerations predicted by formula (2) to selected relations for $M_L = 6$ and 7. Expression (2) has been adapted to be compatible to those of Boore et al. (1997) (top row) and Ambraseys et al. (1996) (middle row), by plotting it against the equivalent average fault distance, $R_{av}$, computed for each epicentral distance and each magnitude as explained in the text and in Fig. 9. In addition, values obtained by (2) were decreased by 15% (see text) to make them comparable with the Boore et al. (1997) curves, as they used the average $\alpha_{max}$ of the two horizontal components. Solid dots indicate minimal epicentral distance (or minimal equivalent fault distance), $D_{min}$, in our data set in the magnitude ranges $6.0 \pm 0.5$ (left) and $7.0 \pm 0.5$ (right). Small white circles are the same for reference relations. R and S indicate rock and soil sites, respectively.

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The rate of amplitude decay with distance given by coefficients $c_3$ is close to the theoretical value for body waves ($c_3 = 1$) and is not significantly different than in other formulas. The rate of increase of $a_{\text{max},b}$ with magnitude ($c_2$) is higher than in ASB96, lower than in BJF97, and similar to SP87. For the vertical component, $c_2$ is somewhat higher than in A95 and AS96, and considerably lower than in SP96.

The global standard deviations of the fit of 0.31 are larger than obtained by other cited authors. This is most probably caused by our current inability to classify recording sites according to the expected soil-induced amplification of strong ground motion. Besides this, we consider the use of epicentral distance instead of the physically more founded station-to-fault distance to be the most important shortcoming which adds to the scatter in the data.

**Fig. 8.** Comparison of peak vertical accelerations predicted by formula (3) to selected relations for $M_L = 6$ and 7. Expression (3) has been adapted to be compatible to those of Ambraseys and Simpson (1996) and Ambraseys (1995) (top), by plotting it against the equivalent average fault distance, $R_{\text{eq}}$, computed for each epicentral distance and each magnitude as explained in the text and in Fig. 9. Solid dots indicate minimal epicentral distance (or equivalent fault distance), $D_{\text{min}}$, in our data set in the magnitude ranges $6.0 \pm 0.5$ (left) and $7.0 \pm 0.5$ (right). R and S indicate rock and soil sites, respectively.
Fig. 9. Schematic presentation explaining the definition of equivalent fault distance, $R_{av}$, $S_1$, $S_2$ – stations, $R_1$, $R_2$ – shortest distance to the fault projection (fault distance), $E$ – epicentre, $D$ – epicentral distance. The rectangle represents the projection of the ruptured part of the fault to the earth's surface. Its length ($L$) and width ($W$) depend on the magnitude and the dip of the fault. $R_{av}$ is then defined for the given magnitude and epicentral distance as the mean of all possible $R_i$ along the circle of radius $D$ (see text for other details).

5. CONCLUSIONS

The proposed peak acceleration attenuation relations to be used in the Dinarides region yield, within the distance range covered by the data, values comparable to the ones obtained by the reference attenuation laws. Judging by the closeness of predicted horizontal maximal accelerations to reference curves and the knowledge of geological conditions in the region, the new relations should be regarded as representative of sites falling into the stiff-soil or rock category. Rather large standard errors of the fit could hopefully be reduced by considering local amplification effects, as well as the fault distance instead of epicentral distance. This would increase the usefulness of the empirical attenuation law, and will therefore be the topic of a separate study.

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