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The Modified Mercalli intensity and the geometry of the sedimentary basin as scaling parameters of the frequency dependent duration of strong ground motion

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Several new empirical equations of the frequency dependent duration of strong earthquake ground motion are presented. The duration is considered as being composed of two parts: (1) the duration of strong motion as it is observed at recording stations located on basement rocks, and (2) the prolongation of this duration for stations located on sediments. The first part, called the 'basic duration', is modelled in terms of the Modified Mercalli intensity and (in some cases) the hypocentral distance. The depth of the sediments under the station, the distance from the station to the rocks surrounding it, and the angular measure of the size of those rocks (as seen from the station) are chosen as the parameters for modelling the prolongation of the duration. The new empirical equations are compared (a) with each other, (b) with our previous models which used similar 'prolongation' terms, but the 'basic duration' was expressed in terms of the magnitude of the earthquake and the source-to-station distance, and (c) with models with 'intensity-type' 'basic duration', but with a simplified 'prolongation' term (the geological conditions at the stations are modeled by lumping all the sites into three groups: basement rock, sediments and intermediate geology). This collection of models is found to have good internal consistency. The choice of the proper model depends on the availability of the earthquake and site parameters. The residuals of the empirical regression equations are found to have similar distribution functions for all the models. An explicit functional form for such distributions is proposed, and the frequency dependent coefficients are found for all the models of duration. This allows one to predict (for each set of earthquake and site parameters) the probability of exceedance of any given level of duration of strong ground motion at a given frequency.

INTRODUCTION AND THE PREVIOUS RESULTS

The duration of strong ground motion is one of the important characteristics of the earthquake ground shaking. Knowledge of the duration is necessary to predict the performance of structures and soils during an earthquake excitation. In this work, we present some new empirical equations for modeling the duration of strong ground motion in terms of the Modified Mercalli intensity at the recording station.

Following the works of Trifunac and Brady,[1] Trifunac and Westermo[2–5] and our recent studies,[6–9] we use the definition of duration of a function of motion $f(t)$ (where $f(t)$ is acceleration, velocity or displacement) as a sum of time intervals during which the integral $\int_0^t f^2(\tau)\,d\tau$ has the steepest slope and gains 90% of its final value. The integral $\int_0^t f^2(\tau)\,d\tau$ is a physically meaningful function. For example, $\int_0^t v^2(\tau)\,d\tau$ is proportional to the total energy, transmitted by the seismic waves past the recording point, and the time derivative of this integral gives the power of the seismic excitation as a function of time. The time derivative of $\int_0^t a^2(\tau)\,d\tau$ gives $a^2_{\mathrm{rms}}(t)$. The functional $\int_0^{t_0} a^2(\tau)\,d\tau$ is proportional to the work (per unit mass) done during the time interval from $t = 0$ to $t = t_0$ by all the forces acting on a single degree-of-freedom viciously damped oscillator exited by acceleration $a(t)$. When the length of

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the record t_0 is sufficient to capture all significant motions at the recording site, the functional $\int_0^{t_0} a^2(\tau)\,d\tau$ is related to Arias intensity. The prediction of the response, $f(t)$, of a multi-degree of freedom structure can be expressed[10–12] in terms of the number of peaks of $f(t)$ during the entire history of excitation, the width of the power spectrum of $f(t)$ and by the value of $((1/t_0)\cdot\int_0^{t_0} f^2(\tau)\,d\tau)^{1/2}$.

In the works of some other researchers[13,14] the frequency dependent nature of the source radiation and wave propagation is disregarded. We consider each record filtered through several relatively narrow band-pass filters, and calculate the duration separately in each one of them. In this work, 12 frequency bands with central frequencies changing from $f_0 = 0{\cdot}075$ Hz up to $f_0 = 21$ Hz are used.

Unlike some other physically related definitions of duration,[15,16] our definition considers the strong motion part as being composed of several separate strong motion 'pulses'. This is necessary, because the definition of the duration of strong motion as one continuous time interval is not meaningful for some records.

As in the studies of Trifunac and Brady,[1] Trifunac and Westermo,[2–5] Theofanopulos and Watabe[14] and our previous works,[6–9] we consider the duration of the strong ground motion, *dur*, as the sum of the duration of the rupture process in the source, τ_0, the prolongation τ_Δ, due to dispersion during the propagation from the source to the station, and the prolongation $\tau_{\text{region and site}}$ due to multiple scattering in the sediments and/or soft soils near the recording site:

$$dur = \tau_0 + \tau_\Delta + \tau_{\text{region and site}} \qquad (1)$$

The first two terms, $\tau_0 + \tau_\Delta$, we call the 'basic duration'. It can be modeled in terms of the magnitude of the earthquake and the source-to-station distance[1,3,4,7,8,14] or in terms of the Modified Mercalli intensity of shaking at the recording site.[2,5,9] It was also shown[9] that the consideration of $\tau_0 + \tau_\Delta$ as a function of both Modified Mercalli intensity and the source-to-station distance enables one to derive correlations (which were not considered before) between the duration of strong ground motion and the site intensity. For a fixed intensity, the duration grows when the separation of the source and the recording site increases. For a fixed distance, the dependence of the duration on intensity is more complex. At low frequencies, the duration of strong motion decreases when the intensity increases, and at high frequency it grows with increasing intensity. A smooth transition from one type of dependence to another occurs at intermediate frequencies.

The third term in eqn (1), $\tau_{\text{region and site}}$ (in the following we will shorten this notation to τ_{rs}), can be expressed, for example, through the simplified geological classification parameter s ($s = 2$ for basement rock sites, $s = 0$ for sites located on sediments and $s = 1$ for intermediate sites, as in Trifunac and Brady[17]), and the local soil parameter s_L (as in Seed *et al.*,[18] $s_L = 2$ for deep soil sites, $s_L = 1$ for stiff soil sites and $s_L = 0$ for sites located on 'local rock'). This representation of τ_{rs} was used by Novikova and Trifunac[7,9] and, in less complete form, by Trifunac and Brady,[1] Trifunac and Westermo[2] and Theofanopulos and Watabe.[14] Such an approach, however, may appear to be too rough for the adequate description of the effects which lead to prolongation of duration of strong ground motion at the stations, located on sediments. Westermo and Trifunac[3–5] used the depth of sediments under the recording site, h, instead of the parameter s for the description of the geological conditions at the site and their influence on the duration. In these works, τ_{rs} was considered as a linear function of h, although it was mentioned that such a dependence may not be physically meaningful.

Novikova and Trifunac[8] developed another, more detailed, representation of the term τ_{rs} as a function of (a) the depth of the sediments under the recording station h, (b) the characteristic horizontal dimension of the valley R — the distance from the station to the rocks, which reflect seismic waves coming from the source in the direction of the station, and, thus produce some prolongation of the duration of strong motion, and (c) the angle, subtended at the station by those rocks, ϕ, which characterize the overall 'power' of the horizontal reflections. The last two parameters, R and ϕ, can be estimated, for example, from the 'map showing distribution and configuration of basement rocks in California' by Smith.[19] It was found that τ_{rs} can be modeled as a sum of a linear function of ϕ and a coupled quadratic function of R and h. The latter corresponds to the qualitative analysis of how the duration should depend on the horizontal or vertical dimensions of the sedimentary deposits. The duration increases with an increase in these dimensions up to some intermediate values of h and R, because of the delayed arrivals of the waves which experienced reflections inside or at the boundary of the sedimentary valley. Further increase in h and R causes a decrease in the duration due to attenuation of the late arrivals, which have propagated along longer paths. The described form of τ_{rs} was used together with the 'basic duration' $\tau_0 + \tau_\Delta$ expressed in terms of the earthquake magnitude and epicentral distance.

In this paper, we first present new empirical regression equations for the duration of strong ground motion by combining the representation of τ_{rs} as a function of h, R and ϕ with the 'basic duration' $\tau_0 + \tau_\Delta$ expressed in terms of the Modified Mercalli intensity (and, in some cases, the hypocentral distance). Depending on the earthquake and site parameters available, the proper model can be chosen from the set of models presented in this paper and in the paper by Novikova and Trifunac.[9] The algorithm for choosing the model and all the regression equations are given in a form suitable for routine calculations of duration. Comparing all the new models with each other and with some of our previous models, we find good internal consistency of the whole set of 'intensity-type' empirical equations for duration of strong ground motion.

The second goal of this paper is to study the residuals of the regression models and to find a frequency dependent distribution function of those. When the parameters of the earthquake and the site are given, the average duration of strong motion at each frequency band can be calculated. Using it and the distribution function of the residuals, the frequency dependent probability of exceedance of any given level of duration can be found. These results can be used in the probabilistic assessments of seismic risk.

THE STRONG MOTION DATA SET

We use the same database as in Novikova and Trifunac.[6–9] The data set, available to all other investigators, cited in the previous session, was less abundant and less homogeneous. Our database has 486 vertical and 984 horizontal components of acceleration, velocity and displacement, generated by 106 earthquakes and recorded by strong motion accelerometers at 283 different sites, located in the Western USA and, primarily, in California. These data are described by Lee and Trifunac,[20] and the methods employed in the band-pass filtering and in the calculation of the duration of strong ground motion in each of the 12 frequency bands are presented by Novikova and Trifunac.[6] The durations of strong motion, obtained for the acceleration, velocity and displacement are treated together as one homogeneous set of data. This is possible due to the narrow frequency bands used. Only carefully selected data were included in the analysis. Each channel of acceleration, velocity and displacement of each record was analyzed separately. Cases where the duration of strong motion was obviously longer than the length of the recording were not included in the analysis. Also, cases with too low signal to noise ratio were disregarded.

The database covers the range of the Modified Mercalli intensity, I_{MM}, from II to X. The coverage, is, however, not uniform: 90% of the data points have I_{MM} equal to V, VI or VII. Only about one third of all the records have the Modified Mercalli intensity, I_{MM}, actually observed at the site. The missing values of I_{MM} were estimated by using the equation, proposed by Lee and Trifunac.[21] They used the earthquake magnitude, the geological site indicator variable s and some 'representative distance' as parameters in their equation.

For the purpose of a better understanding of the nature of the dependence of the duration of strong ground motion on the Modified Mercalli intensity, we want to include a measure of the source-to-station distance in our regression equations.[9] As much as two thirds of the I_{MM} values in the database were obtained using the 'representative distance' as a parameter; this distance would be the first candidate to consider in the role of this source-to-station distance. However, we assume that no instrumental data are available (and the duration of strong ground motion should be expressed through the I_{MM} and the site conditions alone), we cannot include the 'representative distance' in our regression equations, because it, by itself, has the magnitude of the earthquake as a parameter. Without using instrumental data from the region of the earthquake, the position of the epicenter can be approximately located by creating a map of the Modified Mercalli intensities and finding the point where I_{MM} reaches its maximum. The hypocentral depth of the source can be found from the teleseismic records. Also, in the regions with a limited seismogenic zone (like the San Andreas fault system in Central and Southern California), the prevailing hypocentral depth can be estimated without much error. This, and the fact that the 'representative distance' is, by definition, close to the hypocentral distance $\Delta' = \sqrt{\Delta^2 + H^2}$, where Δ is the epicentral distance and H is the hypocentral depth, we use Δ' as a parameter in some of our models of duration. For the records in our database, the epicentral distances are uniformly represented in the range $\Delta \leq 50$ km with the number of records available progressively diminishing beyond $\Delta = 60$ km. The prevailing depth of hypocenters is about 5–8 km.

The depth of the sediments under the stations varies from $h = 0$ to $h = 7$ km. The angle, subtended at the recording site by the rocks capable of producing reflections of the seismic waves towards the station, ranges from 5° to 300°, with the majority of cases having $\phi < 180°$. The distance from the recoding station to those rocks varies from $R = 1$ to $R = 75$–80 km. Some additional information about the data set can be found in Novikova and Trifunac.[6]

EMPIRICAL REGRESSION MODELS OF THE DURATION OF STRONG MOTION

Several new models of the duration of strong ground motion are presented in this section. Some of our previous models[8,9] are also shown for comparison. To distinguish between the models we mark each model by the parameters used in it. Thus, $dur = dur(I_{MM}, \Delta', I_{MM}\Delta', s)$ stands for the model of duration which uses the Modified Mercalli intensity I_{MM}, the hypocentral distance Δ', the coupling term $I_{MM}\Delta'$, and the geological site condition s as given parameters. The unknown coefficients of each model were obtained from linear regression analysis, performed separately at each frequency channel. The singular value decomposition method[22] was used to maintain good control over the accuracy of the inversion problem. The numbering of the model coefficients agrees with the one chosen in our previous studies.[6–9]

As in our previous work,[9] we consider two groups of the regression equations: one group explicitly includes the dependence of the duration of strong ground motion on the distance to the source, and the other excludes this dependence. The models of the first type are more descriptive, but are also more region dependent, because the regional dispersion and attenuation laws are 'built into' the frequency dependent regression coefficients.

We consider now the most 'complete' model (of the first type):

$$\begin{Bmatrix} dur^{(h)}(f) \\ dur^{(v)}(f) \end{Bmatrix} = \max\left[\left(\begin{Bmatrix} a_1^{(h)}(f) \\ a_1^{(v)}(f) \end{Bmatrix} + a_{19}(f)\cdot I_{MM} + a_4(f)\cdot\Delta' + a_{20}(f)\cdot I_{MM}\Delta'\right), 1\right]$$

$$+\begin{Bmatrix} [a_5^{(h)}(f)\cdot h + a_6^{(h)}(f)\cdot R + a_7^{(h)}(f)\cdot hR \\ +a_8^{(h)}(f)\cdot R^2 + a_9^{(h)}(f)\cdot h^2 + a_{10}^{(h)}(f)\cdot\phi]_+ \\ [a_5^{(v)}(f)\cdot h + a_6^{(v)}(f)\cdot R + a_7^{(v)}(f)\cdot hR \\ +a_8^{(v)}(f)\cdot R^2 + a_9^{(v)}(f)\cdot h^2 + a_{10}^{(v)}(f)\cdot\phi]_+ \end{Bmatrix} \tag{2a}$$

where the frequency dependent duration of strong motion, $dur(f)$, is measured in seconds, distances Δ', R and h are measured in kilometers and the angle ϕ is measured in degrees. Superscripts (h) and (v) correspond to the horizontal and vertical components of motion respectively. Those frequency dependent coefficients $a_i(f)$, which do not have any superscript, are found to be essentially the same for the horizontal and for the vertical motion. The expression $\max[(\cdot), 1]$ stands for the 'basic duration', and is bounded by 1 s from below to avoid unrealistically small (and negative) values of $\tau_0 + \tau_\Delta$, which may otherwise arise from the model at $I_{MM} \geq$ VIII (for moderate frequencies) or $I_{MM} \leq$ III (for high frequencies) and small Δ'. The poor control of the model output for this combination of parameters is probably caused by the lack of records in the database from very distractive earthquakes in the epicentral areas, and from small earthquakes. The expression with subscript '+' in eqn (2a) represents the frequency dependent term τ_{rs} from eqn. (1). This term should be considered only if the prolongation is positive:

$$[\tau_{rs}(f)]_+ = \begin{cases} \tau_{rs}(f), & \text{if } \tau_{rs}(f) > 0 \\ 0 & \text{otherwise} \end{cases} \tag{2b}$$

The values of R, h and ϕ are assumed to be zero if the station is located on rock.

Table 1 gives the regression coefficients of eqn (2) as

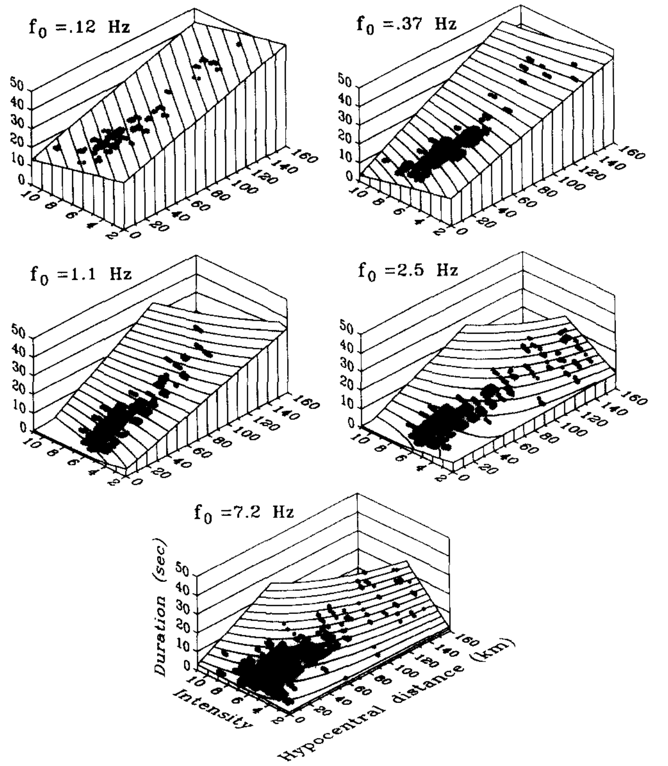

Fig. 1. The 'basic duration' as a function of the Modified Mercalli intensity at the site and the hypocentral distance, calculated according to model (2) at several frequency channels. The asterisks on the three dimensional surface show the intensities and hypocentral distances of the data points, included in the regression analysis. For the clarity of the picture, the intensity of each data point I_{MM} is shown with an arbitrary shift inside the strip $I_{MM} \pm 0{\cdot}4$. Reliable predictions of the duration of strong ground motion can only be done for those combinations of I_{MM} and Δ', where enough data points were available for construction of the model.

$a_i(f) \pm \sigma_i(f)$, where $\sigma_i^2(f)$ are the variances of the values found. Zero values for a coefficient correspond to the cases when $|\sigma_i/a_i| > 1$. The number of the available data points $N(f)$ is very different at each channel, reflecting the statistical reliability of the regression analysis performed. The average observed duration, dur_{av}, and the standard deviation of the duration, predicted by the model in eqn (2), σ_{dur}, are also listed. Note the strong dependence of dur_{av} on frequency.

Figure 1 shows the dependence of the 'basic duration' on the Modified Mercalli intensity and the hypocentral distance, as it is predicted by the model in eqn (2). This dependence is essentially the same as that found for the models with different[9] 'prolongation term'. The duration always grows with an increase in the hypocentral distance. The growth or decrease of duration as a function of intensity for a fixed distance depends on the frequency of motion and on the distance to the source. Figure 2 gives the prolongation of the duration on sediments, as a function of R and h. As in the case[8] of

Table 1. Results of the regression analysis of the model in eqn (2)

Channel number	f_0 (Hz)	No. of data points $N(f)$	Coefficients a_i and their accuracy ('σ-interval')																	σ_{dur} (s)	dur_{av} (s)
			$a_i^{(h)}$ $\pm\sigma_1^{(h)}$	$a_1^{(v)}$ $\pm\sigma_1^{(h)}$	a_{19} $\pm\sigma_{19}$	a_4 $\pm\sigma_4$	a_{20} $\pm\sigma_{20}$	$a_5^{(h)}$ $\pm\sigma_5^{(h)}$	$a_6^{(h)}$ $\pm\sigma_6^{(h)}$	$a_7^{(h)}$ $\pm\sigma_7^{(h)}$	$a_8^{(h)}$ $\pm\sigma_8^{(h)}$	$a_9^{(h)}$ $\pm\sigma_9^{(h)}$	$a_{10}^{(h)}$ $\pm\sigma_{10}^{(h)}$	$a_5^{(v)}$ $\pm\sigma_5^{(v)}$	$a_6^{(v)}$ $\pm\sigma_6^{(v)}$	$a_7^{(v)}$ $\pm\sigma_7^{(v)}$	$a_8^{(v)}$ $\pm\sigma_8^{(v)}$	$a_9^{(v)}$ $\pm\sigma_9^{(v)}$	$a_{10}^{(v)}$ $\pm\sigma_{10}^{(v)}$		
1	0·075	37	40·8 ±2·0	32·5 ±3·1	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	10·2	38·3
2	0·12	311	27·7 ±5·4	28·2 ±5·7	−1·30 ±0·75	0·182 ±0·019	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	10·1	28·3
3	0·21	962	33·3 ±2·7	35·3 ±2·7	−3·17 ±0·37	0·195 ±0·012	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	7·8	21·4
4	0·37	1364	17·1 ±2·8	17·9 ±2·9	−1·25 ±0·40	0·169 ±0·044	0·012 ±0·007	0·0	0·0	0·0	0·0	0·0	0·0185 ±0·0044	0·0	0·0	0·0	0·0	0·0	0·0162 ±0·0072	7·1	20·7
5	0·63	1182	14·8 ±4·1	18·5 ±4·3	−1·89 ±0·63	0·215 ±0·067	0·013 ±0·011	0·0	0·343 ±0·056	0·0265 ±0·0110	−0·0055 ±0·0008	−0·32 ±0·08	0·0282 ±0·0062	1·49 ±1·14	0·101 ±0·107	0·0657 ±0·0186	−0·0037 ±0·0016	−0·75 ±0·17	0·0265 ±0·0105	7·6	19·4
6	1·1	1472	6·0 ±3·2	9·5 ±3·3	−1·06 ±0·52	0·156 ±0·069	0·018 ±0·011	0·84 ±0·56	0·351 ±0·053	0·0213 ±0·0096	−0·0061 ±0·0008	−0·35 ±0·09	0·0360 ±0·0047	1·16 ±0·81	0·107 ±0·076	0·0520 ±0·0159	−0·0032 ±0·0012	−0·54 ±0·14	0·0310 ±0·0074	6·4	15·7
7	1·7	1879	7·2 ±1·5	10·4 ±1·7	−0·83 ±0·26	0·010 ±0·023	0·027 ±0·004	1·53 ±0·41	0·181 ±0·039	0·0233 ±0·0068	−0·0037 ±0·0006	−0·41 ±0·07	0·0139 ±0·0032	2·41 ±0·60	0·042 ±0·056	0·0246 ±0·0106	−0·0016 ±0·0008	−0·51 ±0·10	0·0	5·4	13·4
8	2·5	2053	6·7 ±1·0	8·1 ±1·1	−0·81 ±0·17	−0·037 ±0·016	0·028 ±0·003	0·0	0·146 ±0·019	0·0053 ±0·0019	−0·0022 ±0·0003	0·0	0·0105 ±0·0021	1·99 ±0·40	0·075 0·037	0·0070 ±0·0068	−0·0015 ±0·0006	−0·32 ±0·06	0·0	3·8	9·8
9	4·2	2295	1·6 ±0·6	2·8 ±0·7	0·05 ±0·11	−0·026 ±0·014	0·027 ±0·002	0·0	0·074 ±0·013	0·0	−0·0009 ±0·0002	0·0	0·0046 ±0·0015	1·30 ±0·27	0·0	0·0	0·0	−0·16 ±0·05	0·0	3·2	7·6
10	7·2	2576	1·0 ±0·5	1·6 ±0·5	0·18 ±0·08	−0·070 ±0·012	0·035 ±0·002	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	2·8	6·4
11	13	1584	−1·1 ±0·5	−1·0 ±0·5	0·46 ±0·08	−0·028 ±0·017	0·027 ±0·003	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	2·3	5·1
12	21	735	−3·4 ±0·7	−3·3 ±0·7	0·75 ±0·12	0·118 ±0·038	0·005 ±0·006	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	2·0	4·2
			1	1	I_{MM}	Δ'	$I_{MM}\Delta'$	h	R	hR	R^2	h^2	ϕ	h	R	hR	R^2	h^2	ϕ		
			horiz	vert				Horizontal component						Vertical component							
			Corresponding parameters																		

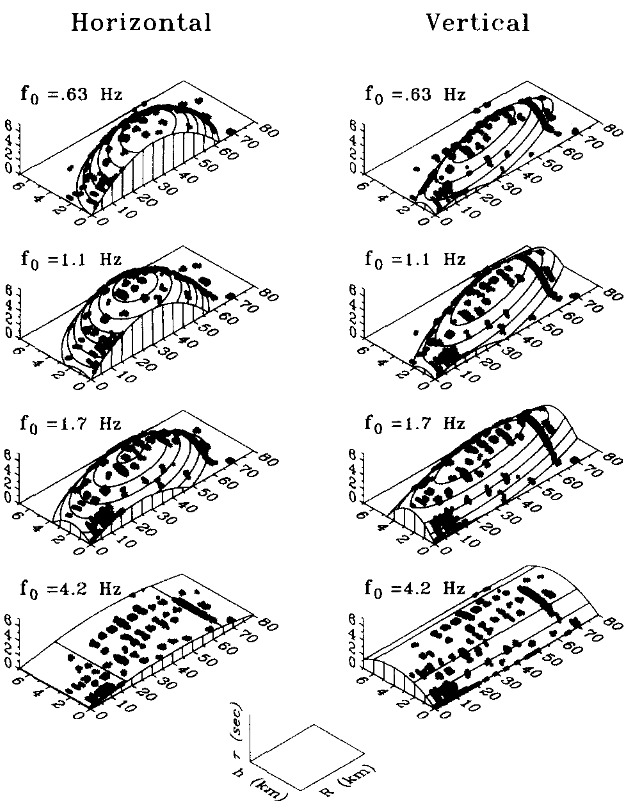

Fig. 2. The 'prolongation' term as a function of the depth of sediments under the recording station, h, and the horizontal characteristic dimension of the sedimentary valley (distance from the station to the rocks), R, is shown (as obtained from the model (2)) for horizontal and vertical component of motion at several frequency bands. The isolines on the three dimensional surface are drawn with 1 s increment, starting from zero level. The asterisks show R and h of the data points, used in the development of the model. Note that practically all the data points correspond to a positive 'prolongation' term.

the 'magnitude-type' 'basic duration', this prolongation can only be noticed at moderate frequencies (0·5–5 Hz), where the seismic waves are not long enough to pass through the sediments without 'noticing' them, and not short enough to become significantly attenuated on the way through the sediments. The maximum prolongation occurs at moderate depths (2–3 km) and widths (30–50 km) of sediments. The additional duration can be as much as 5–6 s at frequencies near 1 Hz. Notice that practically all the data points (shown by asterisks in Fig. 2) fall into the area where $\tau_{rs}(R,h) > 0$. Consequently, $\tau_{rs}(R,h,\phi) = \tau_{rs}(R,h) + \{\text{contribution due to } \phi\}$ is greater than zero for even more data points. This verifies our assumptions about how the presence of a sedimentary basin can influence the duration of strong ground motion.

It is not always possible to obtain complete information about all parameters involved in the description of a sedimentary basin in the 'complete' model (2). We will present here two 'truncated' models. One of them deals with the case when the depth of the sediments under the recording station is not known, but the distribution of rocks around it is available in terms of R and ϕ:

$$\left\{\begin{matrix} dur^{(h)}(f) \\ dur^{(v)}(f) \end{matrix}\right\} = \max\left[\left(\left\{\begin{matrix} a_1^{(h)}(f) \\ a_1^{(v)}(f) \end{matrix}\right\} + a_{19}(f)\cdot I_{MM} + a_4(f)\cdot\Delta' + a_{20}(f)\cdot I_{MM}\Delta'\right), 1\right] + \left\{\begin{matrix} [a_6^{(h)}(f)\cdot R + a_8^{(h)}(f)\cdot R^2 + a_{10}^{(h)}(f)\cdot\phi]_+ \\ [a_6^{(v)}(f)\cdot R + a_8^{(v)}(f)\cdot R^2 + a_{10}^{(v)}(f)\cdot\phi]_+ \end{matrix}\right\} \quad (3a)$$

where all the distances are measured in kilometers. As in eqn (2b),

$$[\cdot]_+ = \max\{0, [\cdot]\} \quad (3b)$$

The values of R and ϕ are assumed to be zero if the recording station is located on basement rock. For the case when the configuration of the rocks is not known, but the depth of the sediments under the recording site is given, the duration of strong ground motion can be estimated from

$$\left\{\begin{matrix} dur^{(h)}(f) \\ dur^{(v)}(f) \end{matrix}\right\} = \max\left[\left(\left\{\begin{matrix} a_1^{(h)}(f) \\ a_1^{(v)}(f) \end{matrix}\right\} + a_{19}(f)\cdot I_{MM} + a_4(f)\cdot\Delta' + a_{20}(f)\cdot I_{MM}\Delta'\right), 1\right] + \left\{\begin{matrix} [a_7^{(h)}(f)\cdot h + a_9^{(h)}(f)\cdot h^2]_+ \\ [a_7^{(v)}(f)\cdot h + a_9^{(v)}(f)\cdot h^2]_+ \end{matrix}\right\} \quad (4a)$$

where

$$[\cdot]_+ = \max\{0, [\cdot]\} \quad (4b)$$

The results of the regression analysis of the last two models are given in Tables 2 and 3, for the models of eqns (3) and (4) respectively. Figure 3 displays the positive contribution of the terms $a_6(f)\cdot R + a_8(f)\cdot R^2$ to the total duration, predicted by eqn (3), for horizontal and vertical motion. In the $dur(I_{MM}, \Delta', I_{MM}\Delta', R, R^2, \phi)$ model (eqn (3)), the additional duration τ_{rs} appears to be 'averaged' over the depth of sediments h, when compared with the term τ_{rs} from the model $dur(I_{MM}, \Delta', I_{MM}\Delta', h, R, hR, R^2, h^2, \phi)$, in eqn (2). A similar averaging effect (this time with respect to R and ϕ) takes place for the other 'truncated' model $dur(I_{MM}, \Delta', I_{MM}\Delta', h, h^2)$, in eqn (4).

For comparison, we recall here the model with a simplified description of the site geology[9] in terms of the

Table 2. Results of the regression analysis of the model in eqn (3)

Channel number	f_0 (Hz)	No. of data points $N(f)$	Coefficients a_i and their accuracy ('σ-interval')											σ_{dur} (s)	dur_{av} (s)
			$a_1^{(h)}$ $\pm\sigma_1^{(h)}$	$a_1^{(v)}$ $\pm\sigma_1^{(v)}$	a_{19} $\pm\sigma_{19}$	a_4 $\pm\sigma_4$	a_{20} $\pm\sigma_{20}$	$a_6^{(h)}$ $\pm\sigma_6^{(h)}$	$a_8^{(h)}$ $\pm\sigma_8^{(h)}$	$a_{10}^{(h)}$ $\pm\sigma_{10}^{(h)}$	$a_6^{(v)}$ $\pm\sigma_6^{(v)}$	$a_8^{(v)}$ $\pm\sigma_8^{(v)}$	$a_{10}^{(v)}$ $\pm\sigma_{10}^{(v)}$		
1	0·075	37	40·8 ±2·0	32·5 ±3·1	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	10·2	38·3
2	0·12	311	27·7 ±5·4	28·2 ±5·6	−1·30 ±0·74	0·182 ±0·019	0·0	0·0	0·0	0·0	0·0	0·0	0·0	10·1	28·3
3	0·21	962	33·3 ±2·7	35·3 ±2·7	−3·17 ±0·37	0·195 ±0·012	0·0	0·0	0·0	0·0	0·0	0·0	0·0	7·8	21·4
4	0·37	1364	17·1 ±2·8	17·9 ±2·9	−1·25 ±0·40	0·169 ±0·044	0·012 ±0·007	0·0	0·0	0·0185 ±0·0044	0·0	0·0	0·0162 ±0·0072	7·1	20·7
5	0·63	1897	7·8 ±2·2	9·2 ±2·3	−0·56 ±0·32	0·096 ±0·032	0·023 ±0·005	0·288 ±0·033	−0·0042 ±0·0005	0·0211 ±0·0039	0·262 ±0·055	−0·0035 ±0·0008	0·0274 ±0·0066	7·4	18·5
6	1·1	2443	6·1 ±1·5	8·7 ±1·6	−0·61 ±0·23	0·049 ±0·024	0·026 ±0·004	0·328 ±0·024	−0·0051 ±0·0004	0·0251 ±0·0029	0·217 ±0·040	−0·0029 ±0·0006	0·0297 ±0·0047	6·2	15·4
7	1·7	2906	4·6 ±1·0	7·0 ±1·0	−0·35 ±0·15	0·033 ±0·017	0·023 ±0·003	0·208 ±0·018	−0·0031 ±0·0003	0·0132 ±0·0021	0·172 ±0·027	−0·0021 ±0·0004	0·0109 ±0·0031	5·0	12·3
8	2·5	3185	4·7 ±0·7	6·4 ±0·7	−0·41 ±0·11	−0·020 ±0·013	0·025 ±0·002	0·141 ±0·013	−0·0020 ±0·0002	0·0078 ±0·0014	0·141 ±0·019	−0·0018 ±0·0003	0·0048 ±0·0022	3·7	9·1
9	4·2	2567	1·9 ±0·6	3·8 ±0·6	−0·03 ±0·10	−0·032 ±0·013	0·029 0·002	0·076 ±0·012	−0·0009 ±0·0002	0·0044 ±0·0014	0·0	0·0	0·0065 ±0·0021	3·2	7·6
10	7·2	2576	1·0 ±0·5	1·6 ±0·5	0·18 ±0·08	−0·070 ±0·012	±0·035 ±0·002	0·0	0·0	0·0	0·0	0·0	0·0	2·8	6·4
11	13	1584	−1·1 ±0·5	−1·0 ±0·5	0·46 ±0·08	−0·028 ±0·017	0·027 ±0·003	0·0	0·0	0·0	0·0	0·0	0·0	2·3	5·1
12	21	735	−3·4 ±0·7	−3·3 ±0·7	0·75 ±0·12	0·118 ±0·038	0·005 ±0·006	0·0	0·0	0·0	0·0	0·0	0·0	2·0	4·2
			1	1	I_{MM}	Δ'	$I_{MM}\Delta'$	R	R^2	ϕ	R	R^2	ϕ		
			horiz	vert				Horizontal			Vertical				
			Corresponding parameters												

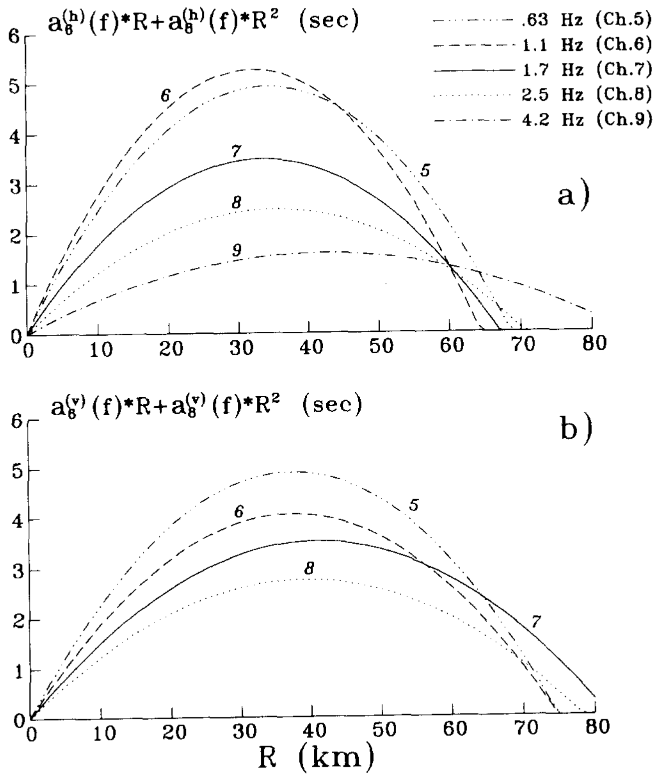

Fig. 3. Prolongation of duration of strong motion as a function of the horizontal characteristic dimension of the sedimentary valley, R, as predicted by the model (3): (a) horizontal component; (b) vertical component. This 'truncated' model preserves the main features of the 'complete' model (2) (Fig. 2) regarding the behavior of the 'prolongation' term.

parameter s:

$$\begin{Bmatrix} dur^{(h)}(f) \\ dur^{(v)}(f) \end{Bmatrix} = \max\left[\left(\begin{Bmatrix} a_1^{(h)}(f) \\ a_1^{(v)}(f) \end{Bmatrix} + a_{19}(f)\cdot I_{MM} + a_4(f)\cdot\Delta' + a_{20}(f)\cdot I_{MM}\Delta'\right), 1\right] + a_{13}(f)\cdot S^{(1)} + a_{14}(f)\cdot S^{(0)} \qquad (5a)$$

where

$$S^{(1)} = \begin{cases} 1, & \text{if } s = 1, \\ 0, & \text{if } s \neq 1, \end{cases} \qquad S^{(0)} = \begin{cases} 1, & \text{if } s = 0 \\ 0, & \text{if } s \neq 0 \end{cases} \qquad (5b)$$

The value $s = 0$ corresponds to a site on sediments, $s = 2$ stands for the site located on basement rock, and $s = 1$ designates intermediate sites. In the same paper we also presented the model which includes the dependence of the duration on the local soil conditions as well as on the site geology. However, we find it more appropriate to use the model in eqn (5) for comparison with eqns (2)–(4), because the description of the term τ_{rs} as a function of h, R and ϕ is more likely to correspond to the geological scale alone, than to the local soil and the geology together.[8] Figure 4 compares the frequency dependent coefficients, involved in the calculation of the 'basic duration', to those obtained from the regression analysis of models (2)–(5). All the coefficients are shown bounded by their 'σ-intervals'. Good agreement in the representation of the 'basic duration' by different models can be noticed.

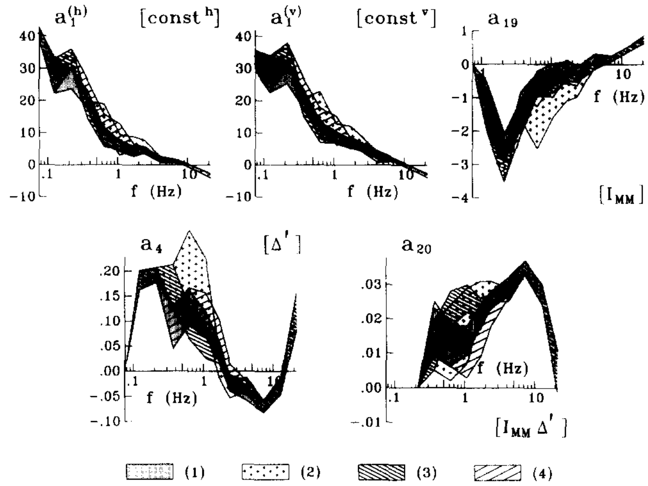

Fig. 4. 'σ-intervals' of the regression coefficients, which define the 'basic duration', plotted versus central frequency of the channels: (1) mdoel $dur(I_{MM}, \Delta', I_{MM}\Delta', s)$, eqn (5); (2) model $dur(I_{MM}, \Delta', I_{MM}\Delta', H, R, hR, R^2, h^2, \phi)$, eqn (2); **(3) model** $dur(I_{MM}, \Delta', I_{MM}\Delta', R, R^2, \phi)$, **eqn (3); (4) model** $dur(I_{MM}, \Delta', I_{MM}\Delta', h, h^2)$, **eqn (4).**

We turn now to the models of the second type. These models, in contrast with eqns (2)–(5) do not have any source-to-station distance among their parameters. We present here three counterparts of eqns (2)–(4):

$$\begin{Bmatrix} dur^{(h)}(f) \\ dur^{(v)}(f) \end{Bmatrix} = \max\left[\left(\begin{Bmatrix} a_1^{(h)}(f) \\ a_1^{(v)}(f) \end{Bmatrix} + a_{19}(f)\cdot I_{MM}\right), 1\right] + \begin{Bmatrix} [a_5^{(h)}(f)\cdot h + a_6^{(h)}(f)\cdot R + a_7^{(h)}(f)\cdot hR \\ \quad + a_8^{(h)}(f)\cdot R^2 + a_9^{(h)}(f)\cdot h^2 + a_{10}^{(h)}(f)\cdot\phi]_+ \\ [a_5^{(v)}(f)\cdot h + a_6^{(v)}(f)\cdot R + a_7^{(v)}(f)\cdot hR \\ \quad + a_8^{(v)}(f)\cdot R^2 + a_9^{(v)}(f)\cdot h^2 + a_{10}^{(v)}(f)\cdot\phi]_+ \end{Bmatrix} \qquad (6)$$

$$\begin{Bmatrix} dur^{(h)}(f) \\ dur^{(v)}(f) \end{Bmatrix} = \max\left[\left(\begin{Bmatrix} a_1^{(h)}(f) \\ a_1^{(v)}(f) \end{Bmatrix} + a_{19}(f)\cdot I_{MM}\right), 1\right] + \begin{Bmatrix} [a_6^{(h)}(f)\cdot R + a_8^{(h)}(f)\cdot R^2 + a_{10}^{(h)}(f)\cdot\phi]_+ \\ [a_6^{(v)}(f)\cdot R + a_8^{(v)}(f)\cdot R^2 + a_{10}^{(v)}(f)\cdot\phi]_+ \end{Bmatrix} \qquad (7)$$

and

$$\begin{Bmatrix} dur^{(h)}(f) \\ dur^{(v)}(f) \end{Bmatrix} = \max\left[\left(\begin{Bmatrix} a_1^{(h)}(f) \\ a_1^{(v)}(f) \end{Bmatrix} + a_{19}(f)\cdot I_{MM}\right), 1\right] + \begin{Bmatrix} [a_7^{(h)}(f)\cdot h + a_9^{(h)}(f)\cdot h^2]_+ \\ [a_7^{(v)}(f)\cdot h + a_9^{(v)}(f)\cdot h^2]_+ \end{Bmatrix} \qquad (8a)$$

where, as before, all the distances are measured in kilometers, the values of h, R and ϕ are assumed to be

Table 3. Results of the regression analysis of the model in eqn (4)

Channel number	f_0 (Hz)	No. of data points $N(f)$	Coefficients a_i and their accuracy ('σ-interval')									σ_{dur} (s)	dur_{av} (s)
			$a_{1(h)}^{(h)}$ $\pm\sigma_1^{(h)}$	$a_{1(h)}^{(h)}$ $\pm\sigma_1^{(h)}$	a_{19} $\pm\sigma_{19}$	a_4 $\pm\sigma_4$	a_{20} $\pm\sigma_{20}$	$a_{5(\eta)}^{(h)}$ $\pm\sigma_5^{(\eta)}$	$a_{9(h)}^{(h)}$ $\pm\sigma_9^{(h)}$	$a_{5(v)}^{(v)}$ $\pm\sigma_5^{(v)}$	$a_{9(v)}^{(v)}$ $\pm\sigma_9^{(v)}$		
1	0·075	37	40·8 ±2·0	32·5 ±3·1	0·0	0·0	0·0	0·0	0·0	0·0	0·0	10·2	38·3
2	0·12	311	27·7 ±5·4	28·2 ±5·7	−1·30 ±0·75	0·182 ±0·019	0·0	0·0	0·0	0·0	0·0	10·1	28·3
3	0·21	962	33·3 ±2·7	35·3 ±2·7	−3·17 ±0·37	0·195 ±0·012	0·0	0·0	0·0	0·0	0·0	7·8	21·4
4	0·37	1499	23·8 ±2·6	24·2 ±2·6	−1·73 ±0·39	0·084 ±0·040	0·018 ±0·007	0·0	0·0	0·0	0·0	7·3	21·0
5	0·63	2035	13·7 ±2·1	15·6 ±2·1	−0·62 ±0·32	0·134 ±0·033	0·012 ±0·006	0·0	0·0	0·0	0·0	7·8	18·7
6	1·1	1612	9·9 ±2·7	12·4 ±2·8	−0·55 ±0·43	0·122 ±0·035	0·009 ±0·006	1·73 ±0·45	−0·30 ±0·08	1·83 ±0·67	−0·28 ±0·12	7·6	16·7
7	1·7	1930	4·8 ±1·5	7·0 ±1·6	−0·12 ±0·25	0·080 ±0·023	0·013 ±0·004	1·76 ±0·33	−0·26 ±0·06	2·07 ±0·48	−0·30 ±0·09	5·9	13·6
8	2·5	2107	4·7 ±1·0	5·6 ±1·1	−0·26 ±0·17	−0·001 ±0·016	0·021 ±0·003	0·85 ±0·22	−0·08 ±0·04	1·70 ±0·32	−0·22 ±0·06	4·2	10·0
9	4·2	2411	1·5 ±0·6	1·5 ±0·7	0·22 ±0·10	−0·032 ±0·013	0·028 ±0·002	0·0	0·0	1·43 ±0·29	−0·18 ±0·05	3·3	7·6
10	7·2	2576	1·0 ±0·5	1·6 ±0·5	0·18 ±0·08	−0·070 ±0·012	0·035 ±0·002	0·0	0·0	0·0	0·0	2·8	6·4
11	13	1584	−1·1 ±0·5	−1·0 ±0·5	0·46 ±0·08	−0·028 ±0·017	0·027 ±0·003	0·0	0·0	0·0	0·0	2·3	5·1
12	21	735	−3·4 ±0·7	−3·3 ±0·7	0·75 ±0·12	0·118 ±0·038	0·005 ±0·006	0·0	0·0	0·0	0·0	2·0	4·2
			1	1	I_{MM}	Δ'	$I_{MM}\Delta'$	h	h^2	h	h^2		
			horiz	vert				Horizontal		Vertical			
			Corresponding parameters										

zero if the site is located on rock and

$$[\cdot]_+ = \max\{0, [\cdot]\} \qquad (6b, 7b, 8b)$$

For comparison, the counterpart of eqn (5), i.e. the model[8] $dur(I_{MM}, s)$ is used:

$$\begin{Bmatrix} dur^{(h)}(f) \\ dur^{(v)}(f) \end{Bmatrix} = \max\left[\left(\begin{Bmatrix} a_1^{(h)}(f) \\ a_1^{(v)}(f) \end{Bmatrix} + a_{19}(f)\cdot I_{MM}\right), 1\right] + a_{15}(f)\cdot(2-s) \qquad (9)$$

Figure 5 gives the 'σ-intervals' of the first three coefficients (which define the 'basic duration') for each of the models (6)–(9) (see also Tables 4–6). The general agreement between all four models is good. Some spread of $a_i(f)$ for different models can probably be explained by uneven representation of various site parameters in the database. This, for example, can bias slightly the 'prolongation' term of the rough model (9), and, consequently, change the 'basic duration' for this model.

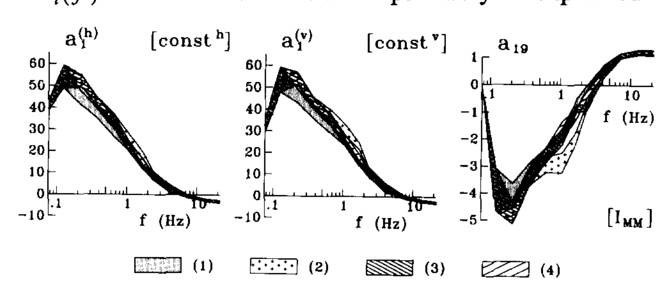

Fig. 5. 'σ-intervals' of the regression coefficients, which define the 'basic duration', plotted versus central frequency of the channels: (1) model $dur(I_{MM}, s)$, eqn (9); (2) model $dur(I_{MM}, h, R, hR, R^2, h^2, \phi)$, eqn (6); (3) model $dur(I_{MM}, R, R^2, \phi)$, eqn (7); (4) model $dur(I_{MM}, h, h^2)$, eqn (8).

We have discussed so far only the comparison of the 'basic duration' coefficients, with those obtained from different models of duration. Next we demonstrate that the representation of the 'prolongation' term by various models is also consistent. First, we consider τ_{rs} as a function of R, h and ϕ. This type of 'prolongation' term is used in models (2) and (6). For comparison, we recall the model[8] with the same τ_{rs}, but a 'magnitude-type' 'basic duration'

$$\begin{Bmatrix} dur^{(h)}(f) \\ dur^{(v)}(f) \end{Bmatrix} = \begin{Bmatrix} a_1^{(h)}(f) \\ a_1^{(v)}(f) \end{Bmatrix} + a_2(f)\cdot\bar{M} + a_3(f)\cdot\bar{M}^2 + a_4(f)\cdot\Delta + \begin{Bmatrix} [a_5^{(h)}(f)\cdot h + a_6^{(h)}(f)\cdot R + a_7^{(h)}(f)\cdot hR \\ \quad + a_8^{(h)}(f)\cdot R^2 + a_9^{(h)}(f)\cdot h^2 + a_{10}^{(h)}(f)\cdot\phi]_+ \\ [a_5^{(v)}(f)\cdot h + a_6^{(v)}(f)\cdot R + a_7^{(v)}(f)\cdot hR \\ \quad + a_8^{(v)}(f)\cdot R^2 + a_9^{(v)}(f)\cdot h^2 + a_{10}^{(v)}(f)\cdot\phi]_+ \end{Bmatrix} \qquad (10a)$$

where the epicentral distance, Δ, depth of sediments,

Table 4. Results of the regression analysis of the model in eqn (6)

Channel number	f_0 (Hz)	No. of data points $N(f)$	Coefficients a_i and their accuracy ('σ-intervals')															σ_{dur} (s)	dur_{av} (s)
			$a_1^{(h)}$ $\pm\sigma_1^{(h)}$	$a_1^{(v)}$ $\pm\sigma_1^{(v)}$	a_{19} $\pm\sigma_{19}$	$a_5^{(h)}$ $\pm\sigma_5^{(h)}$	$a_6^{(h)}$ $\pm\sigma_6^{(h)}$	$a_7^{(h)}$ $\pm\sigma_7^{(h)}$	$a_8^{(h)}$ $\pm\sigma_8^{(h)}$	$a_9^{(h)}$ $\pm\sigma_9^{(h)}$	$a_{10}^{(h)}$ $\pm\sigma_{10}^{(h)}$	$a_5^{(v)}$ $\pm\sigma_5^{(v)}$	$a_6^{(v)}$ $\pm\sigma_6^{(v)}$	$a_7^{(v)}$ $\pm\sigma_7^{(v)}$	$a_8^{(v)}$ $\pm\sigma_8^{(v)}$	$a_9^{(v)}$ $\pm\sigma_9^{(v)}$	$a_{10}^{(v)}$ $\pm\sigma_{10}^{(v)}$		
1	0·075	37	40·8 ±2·0	32·5 ±3·1	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	10·2	38·3
2	0·12	311	54·1 ±5·2	53·6 ±5·6	−3·88 ±0·79	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	11·5	28·3
3	0·21	962	52·3 ±2·7	54·2 ±2·8	−4·74 ±0·40	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	8·7	21·4
4	0·37	1399	42·8 ±1·9	43·9 ±1·9	−3·45 ±0·28	0·0	0·0	0·0	0·0	0·0	0·0010 ±0·0051	0·0	0·0	0·0	0·0	0·0	0·0	8·2	20·7
5	0·63	1657	35·3 ±2·0	37·6 ±2·5	−2·94 ±0·29	0·0	0·0	0·0	0·0	0·0	0·0163 ±0·0050	1·40 ±1·18	0·0	0·0234 ±0·0111	0·0	−0·48 ±0·16	0·0078 ±0·0124	9·3	18·4
6	1·1	1472	25·3 ±2·3	30·2 ±2·5	−2·86 ±0·37	1·81 ±0·74	0·304 ±0·069	0·0243 ±0·0126	−0·0041 ±0·0010	−0·63 ±0·12	0·0394 ±0·0060	2·61 ±0·91	0·0	0·0254 ±0·0092	0·0	−0·59 ±0·13	0·0264 ±0·0096	8·4	15·7
7	1·7	1879	17·9 ±1·3	23·1 ±1·5	−1·94 ±0·22	1·93 ±0·55	0·204 ±0·052	0·0005 ±0·0091	−0·0019 ±0·0008	−0·41 ±0·09	0·0293 ±0·0042	3·04 ±0·66	0·0	0·0170 ±0·0068	0·0	−0·61 ±0·10	0·0062 ±0·0062	7·3	13·4
8	2·5	2836	9·9 ±0·7	11·7 ±0·8	−0·76 ±0·11	0·0	0·108 ±0·017	0·0	−0·0006 ±0·0003	0·0	0·0187 ±0·0019	2·95 ±0·42	0·0	0·0088 ±0·0043	0·0	−0·48 ±0·07	0·0062 ±0·0039	4·9	9·1
9	4·2	2567	3·7 ±0·6	5·2 ±0·6	−0·39 ±0·10	0·0	0·0	0·0	0·0	0·0	0·0158 ±0·0020	0·0	0·0	0·0	0·0	0·0	0·0165 ±0·0030	4·7	7·6
10	7·2	2576	−0·3 ±0·5	0·5 ±0·6	1·09 ±0·09	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	4·5	6·4
11	13	1584	−2·5 ±0·5	−2·0 ±0·5	1·22 ±0·08	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	3·5	5·1
12	21	735	−3·2 ±0·6	−2·8 ±0·6	1·19 ±0·10	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	2·9	4·2
			1	1	I_{MM}	h	R	hR	R^2	h^2	ϕ	h	R	hR	R^2	h^2	ϕ		
			horiz	vert		Horizontal component						Vertical component							
			Corresponding parameters																

Table 5. Results of the regression analysis of the model in eqn (7)

Channel number	f_0 (Hz)	No. of data points $N(f)$	Coefficients a_i and their accuracy ('σ-interval')									σ_{dur} (s)	dur_{av} (s)
			$a_1^{(h)}$ $\pm\sigma_1^{(h)}$	$a_1^{(v)}$ $\pm\sigma_1^{(v)}$	a_{19} $\pm\sigma_{19}$	$a_6^{(h)}$ $\pm\sigma_6^{(h)}$	$a_8^{(h)}$ $\pm\sigma_8^{(h)}$	$a_{10}^{(h)}$ $\pm\sigma_{10}^{(h)}$	$a_6^{(v)}$ $\pm\sigma_6^{(v)}$	$a_8^{(v)}$ $\pm\sigma_8^{(v)}$	$a_{10}^{(v)}$ $\pm\sigma_{10}^{(v)}$		
1	0·075	37	40·8 ±2·0	32·5 ±3·1	0·0	0·0	0·0	0·0	0·0	0·0	0·0	10·2	38·3
2	0·12	311	54·1 ±5·2	53·6 ±5·6	−3·88 ±0·79	0·0	0·0	0·0	0·0	0·0	0·0	11·5	28·3
3	0·21	962	52·3 ±2·7	54·2 ±2·8	−4·74 ±0·40	0·0	0·0	0·0	0·0	0·0	0·0	8·7	21·4
4	0·37	1399	42·8 ±1·9	43·9 ±1·9	−3·45 ±0·28	0·0	0·0	0·0010 ±0·0051	0·0	0·0	0·0	8·2	20·7
5	0·63	1851	33·0 ±1·8	35·3 ±2·0	−2·58 ±0·27	0·0	0·0	0·0170 ±0·0049	0·0	0·0	0·0147 ±0·0080	9·1	18·3
6	1·1	2344	20·9 ±1·4	24·2 ±1·5	−1·99 ±0·21	0·213 ±0·030	−0·0022 ±0·0005	0·0386 ±0·0037	0·130 ±0·050	−0·0006 ±0·0007	0·0391 ±0·0059	7·7	14·9
7	1·7	2805	12·3 ±0·9	15·0 ±1·0	−0·87 ±0·14	0·126 ±0·022	−0·0008 ±0·0003	0·0259 ±0·0027	0·104 ±0·034	−0·0002 ±0·0005	0·0254 ±0·0039	6·2	11·8
8	2·5	3185	10·2 ±0·6	12·4 ±0·7	−0·82 ±0·10	0·107 ±0·016	−0·0005 ±0·0003	0·0188 ±0·0019	0·095 ±0·025	−0·0003 ±0·0004	0·0151 ±0·0028	4·8	9·1
9	4·2	2567	3·7 ±0·6	5·2 ±0·6	0·39 ±0·10	0·0	0·0	0·0158 ±0·0020	0·0	0·0	0·0165 ±0·0030	4·7	7·6
10	7·2	2576	−0·3 ±0·5	0·5 ±0·6	1·06 ±0·09	0·0	0·0	0·0	0·0	0·0	0·0	4·5	6·4
11	13	1584	−2·5 ±0·5	−2·0 ±0·5	1·22 ±0·08	0·0	0·0	0·0	0·0	0·0	0·0	3·5	5·1
12	21	735	−3·2 ±0·6	−2·8 ±0·6	1·19 ±0·10	0·0	0·0	0·0	0·0	0·0	0·0	2·9	4·2
			1	1	I_{MM}	R	R^2	ϕ	R	R^2	ϕ		
			horiz	vert		Horizontal			Vertical				
			Corresponding parameters										

Table 6. Results of the regression analysis of the model in eqn (8)

Channel number	f_0 (Hz)	No. of data points $N(f)$	Coefficients a_i and their accuracy ('σ-interval')							σ_{dur} (s)	dur_{av} (s)
			$a_1^{(h)}$ $\pm\sigma_1^{(h)}$	$a_1^{(h)}$ $\pm\sigma_1^{(h)}$	a_{19} $\pm\sigma_{19}$	$a_5^{(h)}$ $\pm\sigma_5^{(h)}$	$a_9^{(h)}$ $\pm\sigma_9^{(h)}$	$a_5^{(v)}$ $\pm\sigma_5^{(v)}$	$a_9^{(v)}$ $\pm\sigma_9^{(v)}$		
1	0·075	37	40·8 ±2·0	32·5 ±3·1	0·0	0·0	0·0	0·0	0·0	10·2	38·3
2	0·12	311	54·1 ±5·2	53·6 ±5·6	−3·88 ±0·79	0·0	0·0	0·0	0·0	11·5	28·3
3	0·21	962	52·3 ±2·7	54·2 ±2·8	−4·74 ±0·40	0·0	0·0	0·0	0·0	8·7	21·4
4	0·37	1499	42·3 ±1·8	43·2 ±1·8	−3·33 ±0·27	0·0	0·0	0·0	0·0	8·4	21·0
5	0·63	1756	34·6 ±1·9	36·1 ±2·3	−2·59 ±0·29	0·0	0·0	2·37 ±1·01	−0·41 ±0·17	9·3	18·6
6	1·1	1522	22·1 ±2·1	25·6 ±2·2	−1·63 ±0·33	4·00 ±0·54	−0·70 ±0·10	3·17 ±0·81	−0·48 ±0·14	9·0	16·0
7	1·7	1930	14·9 ±1·2	18·1 ±1·4	−1·06 ±0·20	4·19 ±0·41	−0·64 ±0·07	3·59 ±0·61	−0·52 ±0·11	7·5	13·6
8	2·5	2107	8·3 ±0·8	9·7 ±0·9	−0·35 ±0·14	2·74 ±0·29	−0·36 ±0·05	3·23 ±0·42	−0·44 ±0·08	5·5	10·0
9	4·2	1667	1·5 ±0·8	2·6 ±0·9	0·56 ±0·14	2·68 ±0·29	−0·36 ±0·05	3·33 ±0·43	−0·48 ±0·08	4·8	8·4
10	7·2	2576	−0·3 ±0·5	0·5 ±0·6	1·06 ±0·09	0·0	0·0	0·0	0·0	4·5	6·4
11	13	1584	−2·5 ±0·5	−2·0 ±0·5	1·22 ±0·08	0·0	0·0	0·0	0·0	3·5	5·1
12	21	735	−3·2 ±0·6	−2·8 ±0·6	1·19 ±0·10	0·0	0·0	0·0	0·0	2·9	4·2
			1	1	I_{MM}	h	h^2	h	h^2		
			horiz	vert		Horizontal		Vertical			
			Corresponding parameters								

h, and distance to the reflecting rock, R, are measured in kilometers, and the angle ϕ is measured in degrees. $\bar{M}$ is introduced to keep the duration of strong ground motion as a nondecreasing function of magnitude M:

$$\bar{M} = \max\{M, M_{\min}(f)\}, \quad M_{\min}(f) = \frac{-a_2(f)}{2a_3(f)} \tag{10b}$$

and

$$[\cdot]_+ = \max\{0, [\cdot]\} \tag{10c}$$

Figure 6 presents the frequency dependent coefficients, which define the 'prolongation' term $\tau_{rs}(h, R, hR, R^2, h^2, \phi)$ in models (2), (6) and (10). Models (2) and (10) give practically identical results, verifying our assumption that the duration of strong motion can be successfully represented as a function of the Modified Mercalli intensity or the magnitude of the earthquake, and the choice of the model does not influence the accuracy of the 'corection' term which represents the prolongation of duration on sediments. Model (6) has slightly different coefficients in the 'prolongation' term when compared to eqns (2) and (10). This may follow from the oversimplification in describing the 'basic duration' as a function of the Modified Mercalli intensity alone, without any source-to-station distance as a parameter. Especially sensitive are the coefficients dealing with R, i.e. a_6, a_8 and a_7. The roughness of the model does not allow one to resolve well the influence of the horizontal characteristic dimension of the valley, R. The corresponding contribution to the duration gets shifted, in this case, to the term $a_{10} \cdot \phi$. The angle of horizontal reflections, ϕ, is in some sense 'complementary' to R, and it is a less sensitive parameter because it corresponds to the general 'power' of horizontal reflections.

Figure 7 compares $\tau_{rs}(R, R^2, \phi)$ in the models of eqns (3), (7) and the corresponding model[8] for the 'magnitude-type' 'basic duration':

$$\begin{Bmatrix} dur^{(h)}(f) \\ dur^{(v)}(f) \end{Bmatrix} = \begin{Bmatrix} a_1^{(h)}(f) \\ a_1^{(v)}(f) \end{Bmatrix} + a_2(f) \cdot \bar{M} + a_3(f) \cdot \bar{M}^2 + a_4(f) \cdot \Delta + \begin{Bmatrix} [a_6^{(h)}(f) \cdot R + a_8^{(h)}(f) \cdot R^2 + a_{10}^{(h)}(f) \cdot \phi]_+ \\ [a_6^{(v)}(f) \cdot R + a_8^{(v)}(f) \cdot R^2 + a_{10}^{(v)}(f) \cdot \phi]_+ \end{Bmatrix} \tag{11}$$

where $\bar{M}$ and $[\cdot]_+$ are defined as in eqns (10b) and (10c). The same trends as in Fig. 6 can be noticed.

The last comparison we make (Fig. 8), is for the 'prolongation' term, expressed as $\tau_{rs}(h, h^2)$. This type of representation is used in the models of eqns (4), (8) and

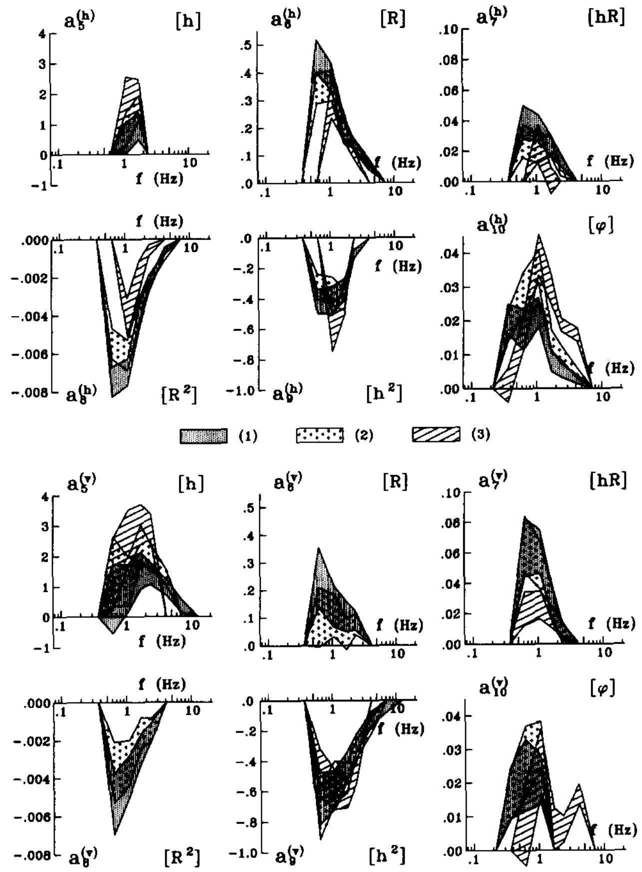

Fig. 6. 'σ-intervals' of the regression coefficients, which define the prolongation of duration on sediments, plotted versus central frequency of the channels: (1) model *dur*(M, M^2, h, R, hR, R^2, h^2, ϕ), eqn (10; (2) model *dur*(I_{MM}, Δ', $I_{MM}\Delta'$, h, R, hR, R^2, h^2, ϕ), eqn (2); (3) model *dur*(I_{MM}, h, R, hR, R^2, h^2, ϕ), eqn (6).

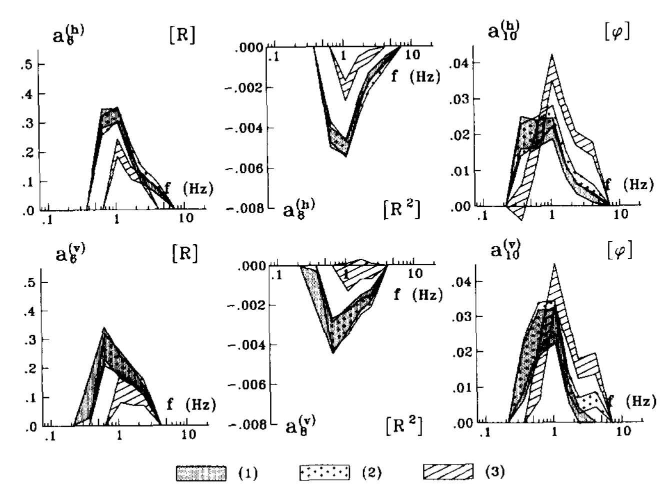

Fig. 7. 'σ-intervals' of the regression coefficients, which define the prolongation of duration on sediments, plotted versus central frequency of the channels: (1) model *dur*(M, M^2, R, R^2, ϕ), eqn (11); (2) model *dur*(I_{MM}, Δ', $I_{MM}\Delta'$, R, R^2, ϕ), eqn (3); (3) model *dur* (I_{MM}, R, R^2, ϕ), eqn (7).

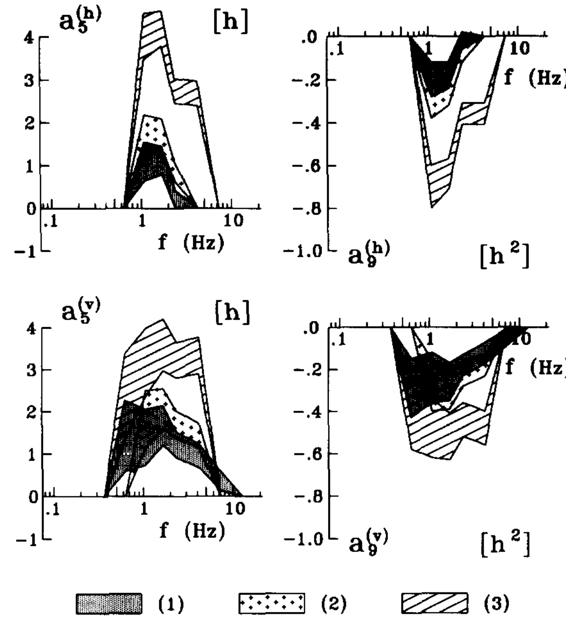

Fig. 8. 'σ-intervals' of the regression coefficients, which define the prolongation of duration on sediments, plotted versus central frequency of the channels: (1) model *dur*(M, M^2, h, h^2), eqn (12); (2) model *dur*(I_{MM}, Δ', $I_{MM}\Delta'$, h, h^2), eqn (4); (3) model *dur*(I_{MM}, h, h^2), eqn (8).

in the corresponding model[8] with the 'magnitude-type' 'basic duration':

$$\begin{aligned}
\begin{Bmatrix} dur^{(h)}(f) \\ dur^{(v)}(f) \end{Bmatrix} &= \begin{Bmatrix} a_1^{(h)}(f) \\ a_1^{(v)}(f) \end{Bmatrix} + a_2(f)\cdot\bar{M} \\
&+ a_3(f)\cdot\bar{M}^2 + a_4(f)\cdot\Delta \\
&+ \begin{Bmatrix} [a_5^{(h)}(f)\cdot h + a_9^{(h)}(f)\cdot h^2]_+ \\ a_5^{(v)}(f)\cdot h + a_9^{(v)}(f)\cdot h^2]_+ \end{Bmatrix}
\end{aligned} \tag{12}$$

where $\bar{M}$ and $[\cdot]_+$ are defined as in eqn (10b) and (10c). Here, again, the 'I_{MM}–Δ'' model (eqn (4)) and the 'M–Δ' model (eqn (12)) give practically the same 'prolongation' term. The 'intensity-type' model which does not include the source-to-station distance as a parameter (eqn (8)), possesses a more pronounced influence of the depth of the sediments on the duration, when compared to the other two models. It could arise from effective coupling of the depth of sediments and the source-to-station distance, because large h in our database corresponds, in average, to larger epicentral and hypocentral distances. The increase in duration which should come from the increase in hypocentral distance cannot be 'recognized' by the model (*dur*I_{MM}, h, h^2) (eqn (8)) as the increase in the 'basic duration'. Instead, this increase is picked up by the 'prolongation' term $a_5\cdot h + a_9\cdot h^2$, making it larger than it is supposed to be.

Having such a variety of models, it is important to know which of them should be used in each particular situation. Figure 9 presents the chart for choosing the

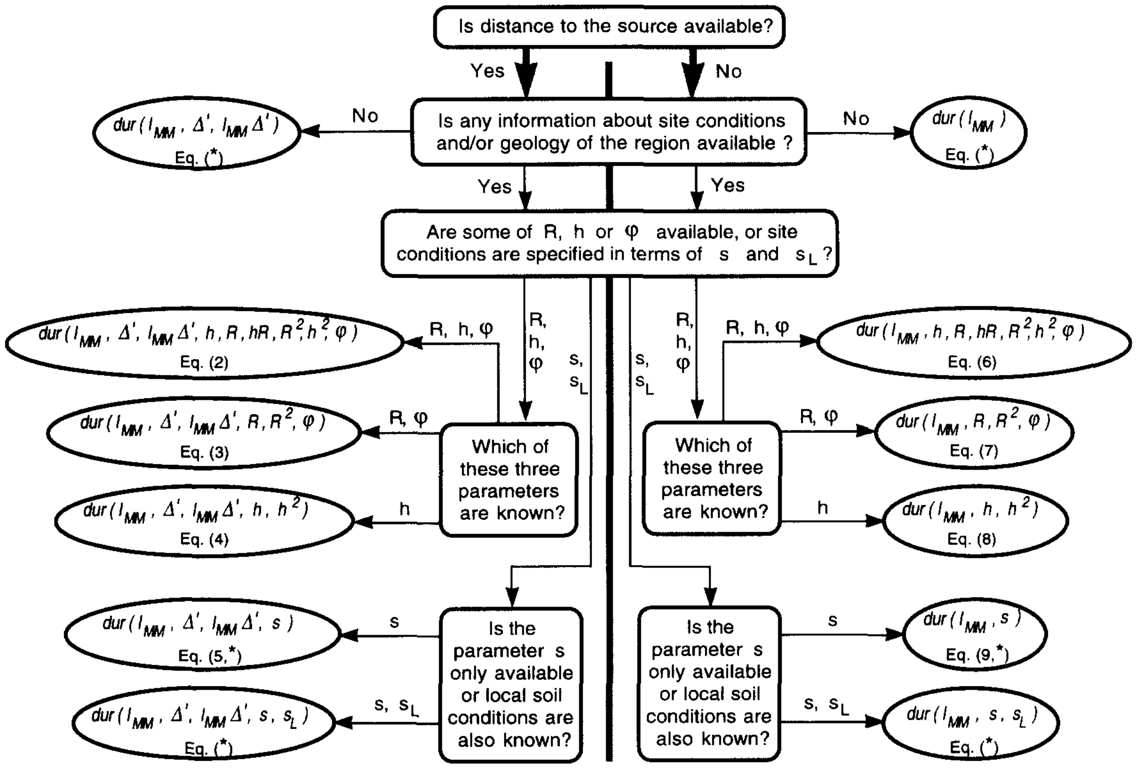

Fig. 9. The algorithm for choosing the proper model, based on what earthquake and site parameters are available. Each model is marked by the equation number. The stars designate those models which were introduced in Novikova and Trifunac.[9] The chart summarizes the 'intensity-type' models only. For the 'magnitude-type' models refer to Novikova and Trifunac.[7,8]

proper model, based on what earthquake and site parameters are available. The chart summarizes the 'intensity-type' models only. (For the 'magnitude-type' models refer to Novikova and Trifunac.[7,8])

DISTRIBUTION FUNCTION OF THE RESIDUALS

The least-squares minimization, used to fit all the models discussed here, is a maximum likelihood estimator of the parameters, only if the measurement errors (and various 'disturbances' coming from those phenomena, which are not included in the model) are independent and normally distributed with a constant standard deviation. We cannot guarantee that this is the case with our models. Even worse, studying the distribution of the residuals, we can say that their distribution function is definitely not Gaussian. Best of all this distribution can be approximated by one of the most 'heavy-tailed' of all known distribution functions — by the power law distribution. All this, however, does not diminish the quality of our models of duration of strong ground motion. Being not 'the best' according to rigorous mathematics, they still represent very good approximations of the desired quantity for engineering purposes.

We next present some results on the residue statistics. The quantity we study is defined as the ratio of the observed duration of strong ground motion, dur_{obs}, to the duration, predicted by a model, *dur*:

$$\rho = \frac{dur_{obs}}{dur}$$

We found that this quantity is easier to deal with than, for example $dur_{\mathrm{obs}} - dur$, because ρ has a well defined lower bound (zero) and has very similar distributions on all frequency channels. We also found that the distribution function of the 'relative residual' ρ does not depend on the parameters of the models, such as the Modified Mercalli intensity, distance to the source and site conditions. This distribution function, $q(\rho)$, is very similar for different models. We approximate it by:

$$q(\rho) = \frac{1}{\eta} \cdot \frac{\rho^{\mathrm{b}}}{a + \rho^{\mathrm{c}}} \tag{13a}$$

where η is the normalizing coefficient:

$$\eta = a^{(b+1)/c-1} \cdot \frac{\pi}{c} \cdot \left[\sin \frac{(b+1)\pi}{c}\right]^{-1} \tag{13b}$$

The coefficients *a*, *b* and *c* should be adjusted for each model at every frequency channel. We choose these coefficients so that the cumulative distribution function

$$P(\rho) = \int_0^{\rho} q(\rho)\,\mathrm{d}\rho \tag{14}$$

stays close to the observed cumulative distribution function $P_{\mathrm{obs}}(\rho)$. This 'closeness' is measured by

$$D = \max\,|P(\rho) - P_{\mathrm{obs}}(\rho)| \tag{15}$$

Table 7 shows the coefficients *a*, *b* and *c* for the

Table 7. Parameters of the distribution function of the residuals (eqn (13)) for the model in eqn (2)

Ch. number	f_0 (Hz)	$N(f)$	a	b	c	D	$D_{0 \cdot 05}$	$D_{0 \cdot 2}$	m	σ
1	0·075	37	2·3	3·5	12·0	0·063	0·223	0·176	1·00	0·27
2	0·12	311	0·6	2·7	7·4	0·033	0·077	0·061	1·02	0·52
3	0·21	962	0·4	3·1	7·4	0·041	0·044	0·035	1·05	0·60
4	0·37	1364	0·9	2·7	8·1	0·028	0·037	0·029	1·01	0·43
5	0·63	1182	1·9	1·5	7·0	0·030	0·040	0·031	0·99	0·48
6	1·1	1472	1·6	1·6	6·8	0·015	0·035	0·028	1·00	0·50
7	1·7	1879	2·2	1·6	7·5	0·019	0·031	0·025	0·99	0·44
8	2·5	2053	1·9	2·0	7·6	0·023	0·030	0·024	1·03	0·46
9	4·2	2295	2·6	1·5	7·3	0·016	0·028	0·022	1·01	0·46
10	7·2	2576	1·7	1·4	6·5	0·021	0·027	0·021	1·00	0·53
11	13	1584	1·3	1·6	6·5	0·022	0·034	0·027	1·00	0·54
12	21	735	1·4	1·5	6·4	0·022	0·050	0·040	1·00	0·54

distribution (13) which minimize D for the most 'complete' 'intensity-type' model (eqn (2)). Figures 10(a) and 10(b) present the quality of fit of the proposed distribution function to the data for channel No. 7 of the model in eqn (2). According to the Kolmogorov–Smirnov criterion, the distribution function $P(\rho)$ should not be disregarded as a candidate for the approximation of the data distribution function $P_{obs}(\rho)$ at the level of significance α, if D from eqn (15) is less than D_α. D_α depends on the number of data points, N (shown in Table 7 for each channel), and on α. The typical value of α used in the literature is 0·05, and $\alpha = 0{\cdot}001$ is used for the model considered to be marginally acceptable.[22] Table 7 shows that our proposed distribution function passes the Kolmogorov–Smirnov test with $\alpha = 0{\cdot}05$ ($D < D_{0 \cdot 05}$) at all channels. At the majority of channels, it passes with an even more severe criterion: $D < D_{0 \cdot 2}$. Table 7 also gives the mean value of the proposed distribution, m, and the variance of it, σ. Note that the mean value of the residuals ρ is equal to 1 by the construction of all our duration models. Thus, we could have reduced the number of coefficients in the distribution function (13) by fixing its mean to be equal to unity. We, however, decided to allow additional flexibility in the coefficients to achieve a better fit in terms of the Kolmogorov–Smirnov test. As a result, the mean of the proposed distribution differs slightly from 1 at some channels.

Table 8 gives the 'best' values for the coefficients a, b and c for the distribution (13) for the rest of the

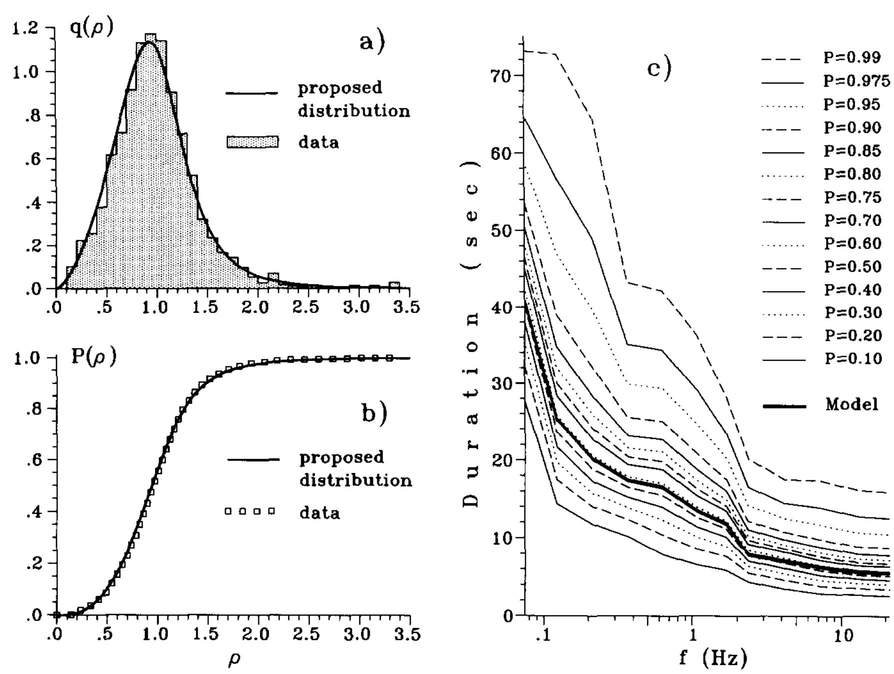

Fig. 10. (a) Comparison of the proposed distribution function $q(\rho)$ (where ρ is the ratio of the observed duration of strong ground motion, to the duration predicted by a model) and the real data for the model in eqn (2), channel no. 7. (b) The same for the cumulative distribution function $P(\rho)$. (c) The duration of strong ground motion predicted by the model in eqn (2) for $I_{MM} = 6$, $\Delta' = 30$ km, $R = 15$ km, $h = 2$ km, $\phi = 30°$ is shown by the bold line. The duration which will not be exceeded with several probability levels at a site with those R, h and ϕ during an earthquake triggered at this Δ' and resulted in shaking of this intensity, is shown by the lines of different type.

Table 8. Coefficients in the distribution function of the residuals (eqn (13)) for five models

Ch. number	f_0 (Hz)	For eqn (3)			For eqn (4)			For eqn (6)			For eqn (7)			For eqn (8)		
		a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
1	0·075	2·3	3·5	12·0	2·3	3·5	12·0	2·3	3·5	12·0	2·3	3·5	12·0	2·3	3·5	12·0
2	0·12	0·6	2·7	7·4	0·6	2·7	7·4	1·9	1·7	7·4	1·9	1·7	7·4	1·9	1·7	7·4
3	0·21	0·4	3·1	7·4	0·4	3·1	7·4	0·4	2·7	6·9	0·4	2·7	6·9	0·4	2·7	6·9
4	0·37	0·9	2·7	8·1	1·2	2·5	8·3	1·1	2·2	7·4	1·1	2·2	7·4	1·1	2·3	7·6
5	0·63	2·5	1·5	7·4	2·1	1·5	7·1	2·7	1·0	6·1	2·7	1·0	6·1	2·7	1·0	6·1
6	1·1	1·8	1·7	7·3	1·7	1·2	6·1	2·0	0·8	5·2	2·6	0·9	5·8	2·2	0·7	5·1
7	1·7	2·8	1·6	8·0	2·2	1·4	7·0	1·6	1·0	5·4	2·2	1·0	5·8	1·8	0·9	5·4
8	2·5	2·5	1·7	7·7	1·1	2·1	7·3	0·8	1·5	5·6	1·2	1·3	5·7	0·7	1·5	5·5
9	4·2	3·1	1·5	7·8	3·5	1·3	7·6	2·2	0·6	4·9	2·2	0·6	4·9	0·6	1·4	5·2
10	7·2	1·7	1·4	6·5	1·7	1·4	6·5	2·0	0·3	4·1	2·0	0·3	4·1	2·0	0·3	4·1
11	13	1·3	1·6	6·5	1·3	1·6	6·5	1·4	0·5	4·2	1·4	0·5	4·2	1·4	0·5	4·2
12	21	1·4	1·5	6·4	1·4	1·5	6·4	1·0	0·6	4·2	1·0	0·6	4·2	1·0	0·6	4·2

models. Having the distribution function ρ, we can predict the duration of strong ground motion which will not be exceeded, with any given probability at a site with known properties during an earthquake with given parameters. For a probability P, the value of ρ_P, such that $P = P(\rho_P)$ can be found from eqns (13) and (14). The duration not to be exceeded with probability P is then $dur_P = dur \cdot \rho_P$, where dur is the duration of strong motion, predicted by the model we choose using the flow-chart in Fig. 9. Figure 10(c) shows dur_P as a function of frequency for several values of P and some fixed model parameters for the model in eqn (2).

SUMMARY AND CONCLUSIONS

This paper summarizes the empirical regression models of the duration of strong ground motion with the Modified Mercalli intensity as the main parameter. Several new models were presented and compared with previously available models, and the whole collection of models was found to have good internal consistency.

The advantage of the new models is that they allow one to take into account a more precise description of the geometry of the sedimentary valley where the recording station is located. Similar models were available before for the models of duration based on the description of the source in terms of the magnitude. New models use the Modified Mercalli intensity as the main parameter instead. This broadens the possibilities for predicting the duration of future earthquakes and helps us to estimate the duration of strong motion from the past earthquakes at noninstrumented sites.

A distribution function of the residuals of the predicted duration has been proposed. This, for example, allows us to obtain an estimate of the duration of strong ground motion which will not be exceeded with any given confidence level, during an earthquake and at a site with known properties.

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