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DURATION OF STRONG GROUND MOTION IN TERMS OF EARTHQUAKE MAGNITUDE, EPICENTRAL DISTANCE, SITE CONDITIONS AND SITE GEOMETRY

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SUMMARY

The physical bases and empirical equations for modelling the duration of strong earthquake ground motion in terms of the earthquake magnitude, the epicentral distance and the geological and local soil site conditions are investigated. At 12 narrow frequency bands, the duration of a function of motion $f(t)$, where $f(t)$ is acceleration, velocity or displacement, is defined as the sum of time intervals during which the integral $\int_0^t f^2(\tau)\,d\tau$ gains a significant portion of its final value. All the records are band-pass filtered through 12 narrow filters and the duration of strong ground motion is studied separately in these frequency bands. It is shown that the duration of strong motion can be modelled as a sum of the source duration, the prolongation due to propagation effects and the prolongation due to the presence of the sediments and local soils. It is shown how the influence of the magnitude on the duration of strong ground motion becomes progressively stronger, in going from low to moderate frequencies, and that the duration is longer for 'soft' than for 'hard' propagation paths, at low and at moderate frequencies. At high frequencies, the nature of the broadening of the strong motion portion of the record with increasing distance is different, and is most likely related to the diffraction and scattering of the short waves by the velocity inhomogeneities along the wave path. It is also shown that the geological and local soil conditions should both be included in the model. The duration can be prolonged by 3·5 sec at a site on a deep sedimentary layer at frequencies near 0·5 Hz, and by as much as 5–6 sec by the presence of soft soil underneath the station, at a frequency of about 1 Hz. An empirical equation for a probabilistic estimate of the discrepancies of the predictions by our models relative to the observed data (distribution function of the residuals) is presented.

INTRODUCTION

The duration of strong earthquake ground motion characterizes the total energy exciting a structure, and may be used to evaluate the rate of this energy input. The significance of the excitation duration is particularly important in the case of non-linear structures, as the number of response cycles is directly related to the duration.[1] The work of Anderson and Bertero[2] shows that large accelerations may not be necessary to drive a structure into the non-linear response. A combination of a moderate acceleration and long duration can result in many cycles of non-linear response.

Udwadia and Trifunac,[3] Amini and Trifunac[4] and Gupta and Trifunac[5–10] developed a method for predicting the probability of exceedance of a given displacement level, a given number of times, at any floor of a multistorey building excited by an earthquake. This probability directly depends on the duration of the strong ground motion. Duration is also used as a parameter in models describing the space–time variations of earthquake ground motion[11] and in the generation of artificial accelerograms.[12–15] The knowledge of the duration of strong ground motion is also necessary for prediction of the response of soils at sites where liquefaction is possible.

In this work, we use some old, and introduce new, simple regression equations which describe the duration of strong ground motion at a site as a function of the earthquake and the site parameters. We develop further the models presented by Trifunac and Westermo,[16–18] who used approximately one-third of the uniformly processed database available to us now.[19] The quality and quantity of our present database has improved through numerous recordings since the late 1970s, and by a careful 'hand' selection of noise-free records. When compared to the studies of Trifunac and Westermo,[16–18] the quality of the new database and more

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careful analysis allow us: (1) to detect quadratic (instead of linear) dependence of duration on magnitude, (2) to analyse dependence of duration on epicentral distance, (3) to consider simultaneously geological and local soil site conditions, and (4) to study the prolongation of duration on sediments using parameters which describe the geometry of the sedimentary basins surrounding the recording stations. Other investigators, who looked at the exponential dependence of the duration on earthquake magnitude, did not include the frequency dependent nature of strong ground motion in their definition of duration,[20,21] nor did they consider records obtained in geologically different regions in the same regression analysis.[22] In all cases, the database available to previous investigators was less abundant or homogeneous.

The main purpose of this study, along with the further development and refinement of the regression models, is to improve the understanding of the nature of the strong ground motion. To this end, the dependence of all the regression coefficients on frequency and the physical phenomena which may have caused this dependence are discussed.

THE DEFINITION OF DURATION

First studies of the dependence of duration on magnitude[23] and on epicentral distance and magnitude[24] did not produce quantitative definitions of duration. Later, duration was defined as the time interval between the first and the last time when the acceleration exceeds the level of 0·05 g ('bracketed' duration[25]), or the time interval during which 95 per cent of the total energy is recorded at the station.[26] Trifunac and Brady[27] define the duration of the excitation function $f(t)$, which can be acceleration, velocity or displacement, as the shortest possible time interval during which 90 per cent of the integral $\int_0^{t_0} f^2(\tau)\,d\tau$ is achieved (t_0 is the length of the digitized record). Bolt[28] suggested that the duration of strong ground motion should be considered separately in several narrow frequency bands. Trifunac and Westermo[16–18,29,30] followed this idea and developed a frequency dependent definition of duration, based on the earlier work of Trifunac and Brady.[27] Kawashima and Aizawa[20] studied bracketed duration and introduced normalized duration, which they defined as the elapsed time between the first and the last acceleration excursion greater than μ times the peak acceleration ($0 < \mu < 1$). McCann and Shah[31] based their definition of duration on the time dependent root-mean-square acceleration, $a_{rms}(t)$. The derivative of $a_{rms}(t)$ identifies the time after which $a_{rms}(t)$ is always decreasing, and this time is used as the upper cut-off time of the strong motion portion. The lower cut-off time can be obtained by applying the above procedure to the record with reversed time. Vanmarcke and Lai[32] introduced their definition using an idealization of the earthquake excitation as a segment of limited duration of a random process with constant spectral density function. Their definition relates the Arias[33] intensity, the maximum acceleration at the site, the predominant period of earthquake excitation and the root-mean-square acceleration to the duration of strong ground motion. Mohraz and Peng[34] introduced the structural frequency and damping into the definition of duration and used a low-pass filter for computing the duration.

The definition of duration, as used by different investigators, progressed from simple bracketed duration towards frequency dependent, structural response oriented functionals, with the seismic energy considered as the main tool in the definition of duration. Many definitions utilize the integral of the type $\int_0^t f^2(\tau)\,d\tau$, where $f(t)$ is acceleration, velocity or displacement, as these integrals have a specific physical meaning.[3–10,27,33] The portions of the record where $\int_0^t f^2(\tau)\,d\tau$ has its fastest growth can be related to the definition of the strong motion part of the excitation. Such a definition of the strong motion duration can then be linked to various physical phenomena whose description involves integrals of this type. Hence, following the works of Trifunac and Westermo,[16–18,29,30] we will accept the definition of duration of a function of motion $f(t)$, where $f(t)$ is acceleration, velocity or displacement, as the sum of time intervals during which the integral $\int_0^t f^2(\tau)\,d\tau$ has the steepest slope and gains a significant portion (90 per cent) of its final value. This definition is of the 'relative' type, i.e. it does not include information about the absolute level of acceleration, while the 'absolute' definitions, like the one of Page *et al.*,[25] do carry this information. However, the knowledge of the frequency dependent duration in this 'relative' sense combined with the information about the Fourier spectral amplitudes[35–37] at all frequencies provides a fairly complete description of the strong motion.

The definition of Trifunac and Westermo,[29] unlike some other physically related definitions,[31,32] considers the strong motion part as being composed of several separate strong motion portions, whose position in the record can be specified. Defining the duration as one continuous time interval is not meaningful for some records. The information on the arrival time of each separate strong motion pulse and of its duration can be used to study the source of the earthquake and the related wave propagation phenomena.[38] Also, this information can be used in further development of the definition of strong motion duration. Thus, considering the energy dissipated by the structure in the time 'gap' between two strong motion pulses and the root-mean-square amplitude of the excitation function in this gap and in the pulses, one can determine whether the structure is going to 'see' two consecutive strong ground motion pulses as one continuous strong excitation.

The duration of strong ground shaking depends on the frequency of the motion. We account for this by studying the duration as a function of various parameters in 12 separate frequency bands (here called channels), with central frequencies of these channels covering the span from $f_0 = 0{\cdot}075$ Hz to $f_0 = 21$ Hz. Each channel is formed by a couple of Ormsby filters whose roll-off and cut-off frequencies are listed in Table I. The procedure for calculating the duration in each channel is summarized in Figure 1. The band-pass filtered signal (corresponding to one of the channels) $f(t)$ by a couple of Ormsby filters is shown at the top of the figure. The result of the integration $I(t) = \int_0^t f^2(\tau)\,\mathrm{d}\tau$ is shown in the centre together with its smoothed version, $I_{\mathrm{sm}}(t)$. The values chosen for corner frequencies of the smoothing filters in each channel are listed in Table I. Being concerned primarily with the relatively long pulses of strong motion, we apply the smoothing filter to the excitation function. The actual width of the pulses shorter than about 3 sec cannot be measured even in the high frequency channels after such a smoothing.[38] The duration of strong ground motion, dur, is defined as the sum of several time intervals $[t_i^{(1)}; t_i^{(2)}]$, where $I_{\mathrm{sm}}(t)$ has the steepest slope. The sum of the gains of $I(t)$ in those time intervals is equal to the fraction μ of the total integral $I(t_0)$, where t_0 is the length of the strong motion record. The portions of the record with the steepest slope of $I_{\mathrm{sm}}(t)$ are identified as those time intervals where the derivative $\mathrm{d}I_{\mathrm{sm}}/\mathrm{d}t$ is bigger than some threshold level ρ_μ (bottom of Figure 1). The value of ρ_μ can be obtained when μ is specified. In this study, we assumed $\mu = 0{\cdot}9$. Some of our empirical models were tested with $\mu = 0{\cdot}75$ and $\mu = 0{\cdot}95$, and no significant differences in the major overall trends were found. From this point on, we will call the duration obtained by the procedure described above as 'observed' duration.

Table I. The properties of the filters used in the two-step process of calculating the frequency dependent duration of strong ground motion

		Step one: band-pass filtering	Step two: smoothing of $\int_0^t f^2(\tau)\,\mathrm{d}\tau$
Channel number	Central frequency f_0 (Hz)	Cut-off and roll-off frequencies of the band-pass filter (Hz)	Corner frequency f_c (Hz)
1	0·075	0·05–0·07; 0·08–0·10	0·038
2	0·12	0·08–0·10; 0·15–0·17	0·06
3	0·21	0·15–0·17; 0·27–0·30	0·11
4	0·37	0·27–0·30; 0·45–0·50	0·14
5	0·63	0·45–0·50; 0·80–0·90	0·17
6	1·1	0·80–0·90; 1·30–1·50	0·20
7	1·7	1·30–1·50; 1·90–2·20	0·23
8	2·5	1·90–2·20; 2·80–3·50	0·26
9	4·2	2·80–3·50; 5·00–6·00	0·28
10	7·2	5·00–6·00; 8·75–10·25	0·30
11	13	8·75–10·25; 16·00–18·00	0·32
12	21	16·00–18·00; 25·00–27·00	0·35

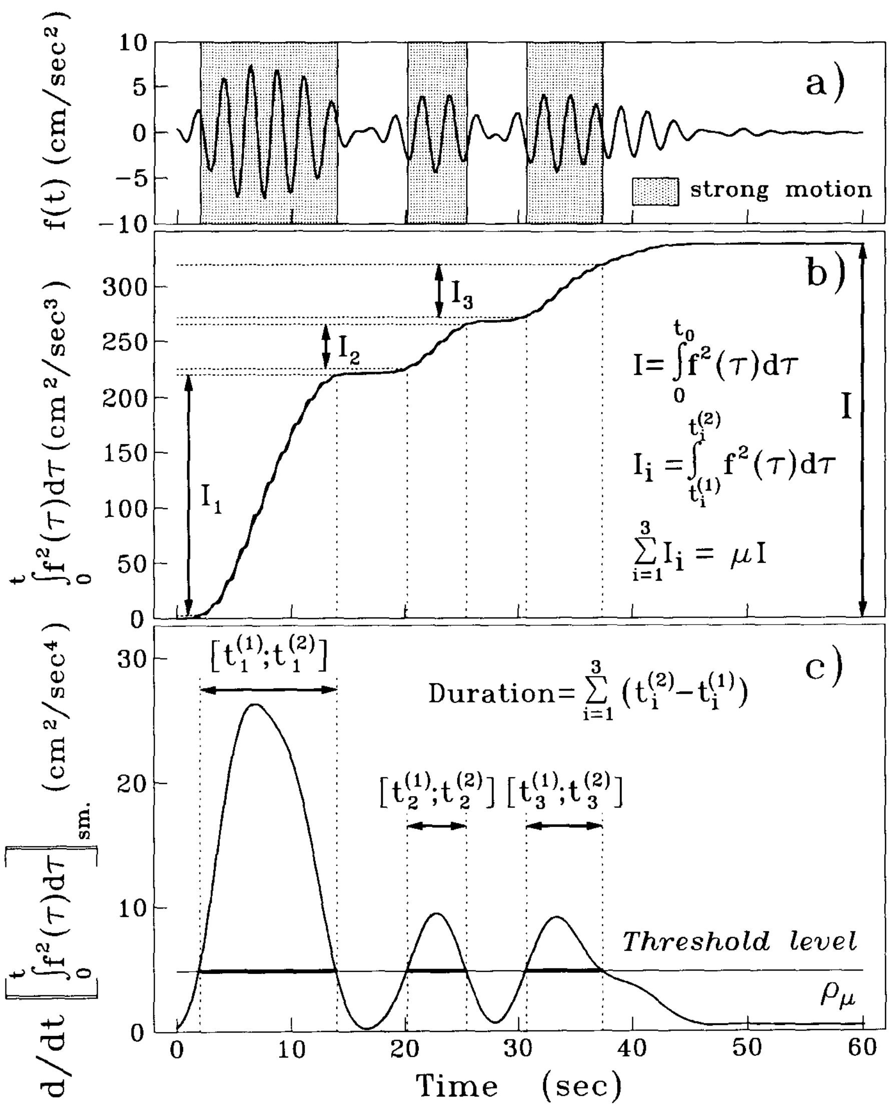

Figure 1. The definition of duration illustrated for the east acceleration component of the Morgan Hill earthquake, band-pass filtered by channel #4 filters (central frequency 0·37 Hz): (a) time history $f(t)$ with strong motion intervals (shaded); (b) $\int_0^t f^2(\tau)\,d\tau$ and its smoothed version; (c) the derivative of the smoothed integral of $f^2(t)$ and its threshold level ρ_μ. The time intervals giving contributions to duration with $\mu = 0{\cdot}9$ are highlighted

THE STRONG MOTION DATA

We used uniformly processed data consisting of three-component 'free field' acceleration records obtained in the Western U.S., primarily in Southern California.[19] Each component of every record was digitized, integrated (to get velocity and displacement) and filtered to be noise-free inside a frequency band which depends on the quality of the record, but is not wider than 0·05–25 Hz. The methods used in digitization and processing of these records are described by Lee and Trifunac.[39,40] This database has 486 vertical and 984 horizontal components of acceleration, velocity and displacement, generated by 106 earthquakes and recorded at 267 different sites.

A large number of these records were generated by the San Fernando earthquake in 1971, which had magnitude $M = 6{\cdot}4$ (we use the 'published' magnitude,[41] which corresponds to the local magnitude scale M_L

when $M \leqslant 6{\cdot}5$ and to surface wave magnitude when $M > 6{\cdot}5$ to 7). Excluding this event, the database has a relatively uniform coverage of magnitudes from $M = 4$ to $M = 6{\cdot}5$ with just a few records available for $M \sim 3$ and $M \geqslant 7$ (Figure 2(a)). The epicentral distances are uniformly represented in the range $\Delta \leqslant 50$ km, with the number of available records progressively diminishing beyond $\Delta = 60$ km (Figure 2(b)). Some information about the recording sites is also available (Table II). We use here the simplified geological classification in terms of the site parameter s. Sites located on sediments are marked by $s = 0$, sites located on geological (basement) rock are labelled by $s = 2$, and $s = 1$ stands for the intermediate sites.[42] We also use the soil classification factor[43] s_L, which describes the sites on a 'local scale', once the properties on the 'geological scale' are specified in terms of the parameter s. For deep soil sites (soil layer deeper than 100 m) $s_L = 2$, and $s_L = 1$ for stiff soil sites (soil layer 15–70 m deep). In both cases, the shear wave velocity in the soil should be less than 800 m/sec. If the shear wave velocity in the soil material exceeds 800 m/sec or the depth of soil is less than 10 m, the site is classified as 'rock', $s_L = 0$. $s_L = 3$ representing deep cohesionless sites as used by Seed[43] are not common in the area studied in this paper. The distribution of sites among different s and s_L is not

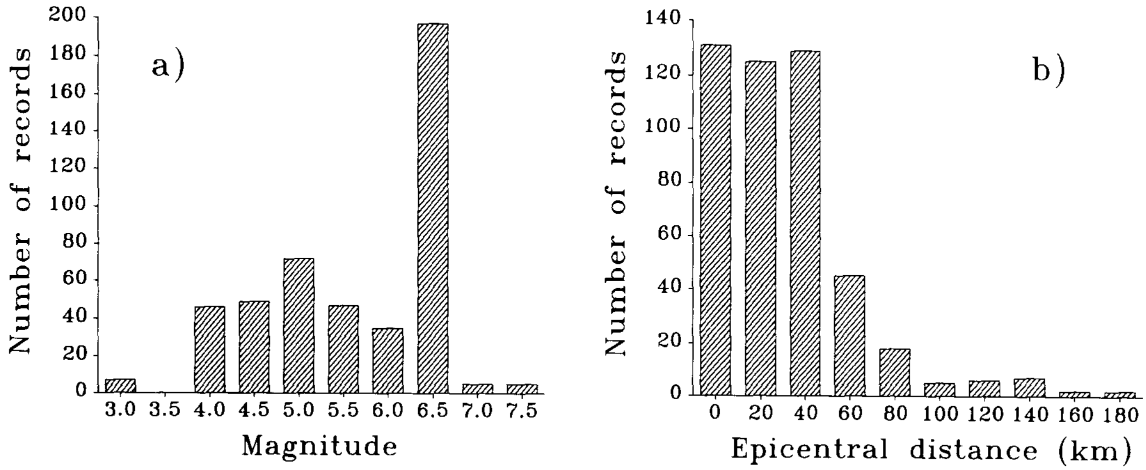

Figure 2. Distribution of the three-component records of good quality (at least one component of acceleration, velocity or displacement in at least one channel was adopted for use in the regression analysis) with respect to: (a) earthquake magnitude; (b) epicentral distance

Table II. The number of the recording stations where the site parameters s and s_L are available. The number of good accelerograph records obtained there is shown in brackets. The totals for a given s exceed the sum of station and records with the same s and different s_L because parameter s_L is not known for some stations

Local soil conditions	Geology: $s = 0$ (sediments)		$s = 1$ (intermediate)		$s = 2$ (basement rock)	
$s_L = 2$ (deep soil)	42	(93)	2	(5)	0	(0)
$s_L = 1$ (stiff soil)	32	(45)	24	(25)	3	(3)
$s_L = 0$ ('rock')	1	(2)	10	(14)	13	(16)
Total for any soil	142	(296)	50	(75)	25	(41)

uniform, with a small number of stations located on geological basement rock and on 'rock' soil sites (Table II). At present, the parameter s_L is not known for many stations. We emphasize the difference between 's' and 's_L' classification: the former describes the geological environment of the site on the scale of several kilometres; the latter characterizes the local soil conditions on the scale of up to 100 m. In addition to the above site classification, we use three other parameters describing the geometry of the sedimentary basin where the site is located. We introduce these parameters later.

The subset of data that can be used to study the duration of strong ground motion was carefully selected from the complete database. The selection procedure[38] we used is based on simple physical considerations and can be summarized as follows. Each channel of acceleration, velocity and displacement of each record was analysed separately. The record $f(t)$ and the integral $\int_0^t f(\tau)\, d\tau$ were used to identify (1) the cases where the duration of strong motion was obviously longer than the length of the recording, and (2) the cases with low signal to noise ratio. Those were not included in the analysis. Figure 3 shows the number of acceleration, velocity and displacement records at each channel adopted for the analysis, separately for the horizontal and for the vertical components. At each channel, data from all three functions (acceleration, velocity and displacement) were used in the analysis as one uniform data set.[38]

REGRESSION MODELS

We consider the duration of strong ground motion as the sum of three terms:

$$\mathrm{dur} = \tau_0 + \tau_\Delta + \tau_{\mathrm{site}} \tag{1}$$

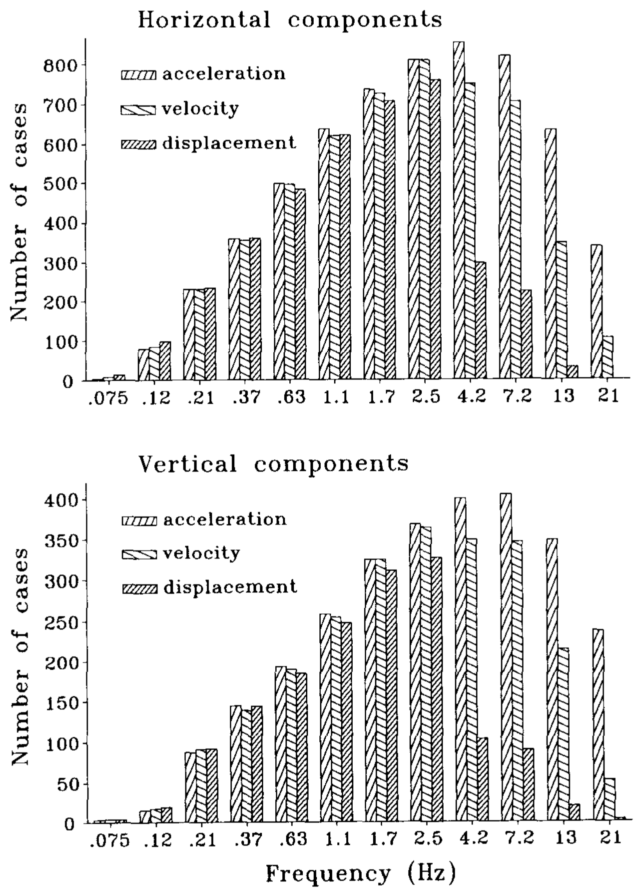

Figure 3. Number of components of band-pass filtered acceleration, velocity and displacement adopted for use in the regression analysis at each frequency band (channel). The channels are identified by their central frequency

where dur is the total duration of acceleration, velocity or displacement, τ_0 stands for the duration of the rupture process at the source, τ_Δ represents the increase in duration due to propagation effects and τ_{site} describes the influence of the geological and local soil site conditions. Several regression equations modelling the duration of strong ground motion will be discussed. For each model, a linear regression analysis was performed separately at each frequency band. The unknown regression coefficients were obtained by the singular value decomposition.[44]

Model dur $= \mathrm{dur}(M, M^2, \Delta)$

We first consider the case when no information about the site conditions is available, and the term τ_{site} is excluded from equation (1). In this case, the duration described by equation (1) should be viewed as the duration on some 'average' site, typical for our database (i.e. typical for Southern California).

The duration of an earthquake source τ_0 may be related to the fault length, whose logarithm is approximately a linear function of magnitude.[45] Although not every earthquake can be described by a fault rupture initialized at one end of the fault and propagating towards the other end, the first estimate of τ_0 could be the length of the source, divided by the average velocity of the dislocation. Thus, the dependence of the source duration τ_0 on the earthquake magnitude M can be assumed to be exponential. There are at least two difficulties in using this exponential dependence in the frequency dependent models of strong motion duration. First, exponential dependence of the rupture time on frequency holds only for relatively high frequencies, since any source can be represented as a point (delta-function in space and time) when observed through a long-wavelength window. At these low frequencies, the rupture time cannot be resolved (using our 'relative' definition of duration) and, thus, should not depend on M at all. Second, exponential dependence of τ_0 on M results in non-linear regression analysis, which may not be stable, especially for noisy data. Thus, we use a quadratic approximation of the exponential function, $\tau_0 \approx a_1 + a_2 \cdot M + a_3 \cdot M^2$, where a_i are unknown coefficients. τ_Δ is an increasing function of Δ, and we assume, following the work of Trifunac and Brady,[27] that $\tau_\Delta = a_4 \cdot \Delta$.

In the case we consider now (no site specific information is available) the regression model has the form

$$\begin{Bmatrix} \mathrm{dur}^{(h)}(f) \\ \mathrm{dur}^{(v)}(f) \end{Bmatrix} = \begin{Bmatrix} a_1^{(h)}(f) \\ a_1^{(v)}(f) \end{Bmatrix} + a_2(f) \cdot \bar{M} + a_3(f) \cdot \bar{M}^2 + a_4(f) \cdot \Delta \tag{2a}$$

where the epicentral distance, Δ, is measured in kilometres and $\bar{M}$ was introduced to make the duration a monotonically increasing function of magnitude.

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

Superscripts (h) and (v) correspond to the horizontal and vertical components of motion. Only the first (constant) coefficient was found to be different for these two directions of motion.

Table III gives the regression coefficients of equation (2) as $a_i(f) \pm \sigma_i(f)$, $i = 1$–4, 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, $\mathrm{dur}_{\mathrm{av}}$, and the standard deviation of the duration, predicted by equation (2), σ_{dur}, are also listed. Note the strong dependence of $\mathrm{dur}_{\mathrm{av}}$ on frequency. The last three columns in Table III will be discussed later.

The duration of strong ground motion does not depend on the magnitude of the earthquake if the frequency of shaking, f, is less than some critical value: $f < f_{\mathrm{cr}} \approx 0{\cdot}25$ Hz ($a_2 = a_3 = 0$ for the first three channels). If the period of the waves employed to 'measure' duration is longer than the characteristic time of the rupture process at the source, τ_0, the dependence of the duration of strong motion, dur, on the length of the source, and likewise on the seismic moment and magnitude, disappears. The critical frequency f_{cr} depends on the quality of the database. When the frequency of motion, f_0, increases, more earthquake sources with corner frequency lower than f_0 participate in the regression and some dependence of τ_0 (and dur) on M can be observed: the linear coefficient $a_2(f)$ becomes different from zero. Further increase of frequency ($f_0 \geqslant 1{\cdot}7$ Hz)

Table III. Results of the regresssion analysis of equation (2) and coefficients in the distribution function of the residuals (equation (4)) for this model

Channel number	f_0 (Hz)	No. of data points $N(f)$	Coefficients a_i and their accuracy ('σ-interval') $a_1^{(h)} \pm \sigma_1^{(h)}$	$a_1^{(v)} \pm \sigma_1^{(v)}$	$a_2 \pm \sigma_2$	$a_3 \pm \sigma_3$	$a_4 \pm \sigma_4$	M_{min}	σ_{dur} (sec)	dur_{av} (sec)	Coefficients in the distribution function of the residuals m	n	k
1	0·075	37	40·8 ± 2·0	32·5 ± 3·1	0·0	0·0	0·0		10·2	38·3	2·3	3·5	12·0
2	0·12	311	19·1 ± 1·1	19·4 ± 1·6	0·0	0·0	0·191 ± 0·018		10·2	28·3	0·7	2·6	7·6
3	0·21	962	11·9 ± 0·6	13·6 ± 0·7	0·0	0·0	0·215 ± 0·012		8·1	21·4	0·4	2·9	7·1
4	0·37	1499	7·8 ± 3·2	8·2 ± 3·2	0·84 ± 0·52	0·0	0·191 ± 0·008		7·4	21·0	1·5	2·4	8·6
5	0·63	2029	1·8 ± 2·0	3·7 ± 2·1	1·51 ± 0·35	0·0	0·184 ± 0·007		7·8	18·7	2·0	1·5	7·0
6	1·1	2618	− 3·6 ± 1·3	− 1·0 ± 1·4	2·10 ± 0·23	0·0	0·149 ± 0·005		6·9	15·6	2·1	1·3	6·7
7	1·7	3099	− 4·1 ± 0·8	− 1·6 ± 0·8	1·90 ± 0·14	0·0	0·123 ± 0·004		5·3	12·4	2·2	1·6	7·5
8	2·5	3359	7·1 ± 1·7	8·7 ± 1·7	− 2·67 ± 0·62	0·41 ± 0·06	0·084 ± 0·003	3·26	3·7	9·0	2·7	1·5	7·4
9	4·2	2714	8·7 ± 1·4	10·0 ± 1·4	− 3·91 ± 0·54	0·57 ± 0·05	0·071 ± 0·003	3·43	3·2	7·6	2·5	1·5	7·1
10	7·2	2553	9·6 ± 1·1	10·1 ± 1·1	− 4·68 ± 0·42	0·66 ± 0·04	0·064 ± 0·003	3·55	2·6	6·4	2·8	1·5	7·2
11	13	1572	6·2 ± 1·1	6·3 ± 1·1	− 3·33 ± 0·42	0·52 ± 0·04	0·055 ± 0·003	3·20	2·0	5·1	3·0	1·5	7·3
12	21	724	10·1 ± 2·1	10·1 ± 2·1	− 4·68 ± 0·84	0·62 ± 0·08	0·056 ± 0·007	3·77	1·8	4·2	6·6	1·2	7·9
			1 horiz	1 vert	M	M^2	Δ						
			Corresponding parameters										

results in all the sources from the database having the corner frequencies lower than f_0. This makes it possible to resolve the quadratic coefficient $a_3(f)$.

The coefficient a_4 scales the duration of strong motion in terms of the epicentral distance. At its maximum (near frequency 0·2 Hz), the value of a_4 corresponds to the increase of duration by 2 sec per each 10 km of epicentral distance, and at $f \approx$ 15–20 Hz this value drops to 0·5 sec per each 10 km. At low and intermediate frequencies, the main contribution to the strong ground motion comes from surface waves, and the increase of the duration with distance can be explained by the dispersion of those waves, travelling through the irregular, but generally 'layered', structure of the upper crust.[38] If $c_{\min}(f)$ and $c_{\max}(f)$ are the effective minimum and maximum phase velocities of the surface waves in the region, and $v_{\min}(f)$ and $v_{\max}(f)$ are the lowest and the highest shear wave velocities in this region, then

$$a_4(f) \approx [c_{\min}(f)]^{-1} - [c_{\max}(f)]^{-1} < [v_{\min}]^{-1} - [v_{\max}]^{-1} \tag{3}$$

For very long surface waves, only one mode of propagation is possible (at the local distances), and for a narrow frequency band only minor dispersion occurs; so $a_4(f) \rightarrow 0$ as $f \rightarrow 0$. Increasing f slightly, we introduce additional modes and the variety of possible phase velocities increases. As a result, $a_4(f)$ grows and reaches its maximum. Further increase in frequency causes effective concentration of the phase velocities of different modes at the smallest shear wave velocity of the region. Then, $c_{\min}(f) \approx v_{\min}$, and as $c_{\max}(f)$ decreases, so does $a_4(f)$.

For high frequencies ($f >$ 5–10 Hz), our data suggest that a_4 does not depend on frequency. The nature of the broadening of the strong motion pulses with distance differs here from the dispersive nature of the low frequency wave propagation. For high frequencies, the strong motion consists primarily of body waves (with some contribution of surface wave energy). In this case, the velocity inhomogeneities (large compared with the wavelength of seismic waves) produce fluctuations in the arrival time of the waves and contribute to an increase of the duration of the strong motion pulses when the travel distance increases.[46] For our data this increase appears to be independent of frequency.

Using a map that shows the distribution of basement rocks on the earth's surface,[47] we characterized the 'hardness' of the transmission path for each pair source–station by the ratio of the portion of epicentral distance covered by rocks, as seen on the surface, to the total epicentral distance. We denote this ratio by ξ, and call paths with high ξ as 'hard' and paths with low ξ as 'soft'. We next make the following assumptions. Let $v_{\max}$ in inequality (3) represent the shear wave velocity in the basement rock at some depth (say 3–7 km), and $v_{\min}$ be the 'effective' shear wave velocity in the 'mixed' top layer, which consists of rocks of various rigidities and sizes and of surface sediments. Now, if we consider the 'soft' and 'hard' paths, then we can assume that $v_{\max}$ should be the same for both path categories, while $v_{\min}$ should be smaller for 'soft' paths than for 'hard' paths. To check the applicability of inequality (3), equation (2) was slightly modified by assuming $a_4 = \alpha + \beta\xi$, i.e. the 'prolongation due to propagation' coefficient is a linear function of the 'hardness' of the path ξ. The regression analysis of this modified model gives practically the same value of the coefficients a_1, a_2 and a_3 as for the original model (2). The dependence of a_4 on frequency is shown in Figure 4 for several values of the parameter ξ in the modified model. The interval $a_4 \pm \sigma_4$, as obtained from the original model (2), is shown for comparison. As expected, $a_4[\xi \approx 0] > a_4[\text{all cases}] > a_4[\xi \approx 1]$. Some reasonable values of the shear wave velocities can be shown to agree with inequality (3) and the results presented in Figure 4. To be more specific, assume $v_{\max} = 4$ km/sec, for example. Then, for the case when a_4 does not depend on ξ, the 'dispersion coefficient' $a_4(f) < 0{\cdot}21$ sec/km, and $v_{\min}$ can be estimated (from equation (3)) to be about 2·2 km/sec. For a 'very soft' path ($\xi = 0$), the coefficient a_4 is bounded by 0·27 sec/km, and $v_{\min} \approx 1{\cdot}9$ km/sec. For 'harder' paths ($\xi \approx 0{\cdot}6$), $a_4 < 0{\cdot}12$ sec/km, which gives $v_{\min} \approx 2{\cdot}7$ km/sec. Consideration of $\xi > 0{\cdot}6$ is not adequate at low frequencies due to the lack of data with such path parameters. Notice that at high frequencies, a_4 practically does not depend on ξ. The reason might be associated with the diffraction and scattering, not with the dispersive nature of the prolongation of the duration at those frequencies.

The constant coefficients $a_1^{(h)}$ and $a_1^{(v)}$ have different meanings for different frequency bands. For channel #1 ($f_0 = 0{\cdot}075$ Hz), $a_1^{(h)}$ and $a_1^{(v)}$, being the only coefficients distinct from zero, give the direct estimate of the duration for the horizontal and for the vertical motions. This estimate does not change with magnitude or epicentral distance. For the second and third channels ($f_0 = 0{\cdot}12$–$0{\cdot}21$ Hz), $a_1^{(h)}$ and $a_1^{(v)}$ give the value of the

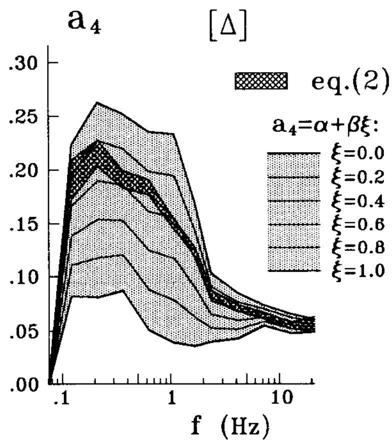

Figure 4. 'σ-interval' of the coefficient $a_4(f)$ in equation (2) (cross-hatched area) and the coefficient a_4 when linear dependence of a_4 on the 'hardness' of the propagation path, ξ, is assumed (shaded zone)

duration at the epicentre of the earthquake, and this value does not depend on the magnitude of the event. For higher frequencies, $a_1(f)$ may not have any physical meaning, because it effectively serves as a constant term in the truncated Taylor expansion of the exponential representation $\tau_0 = \tau_0(M)$. However, by comparing $a_1^{(h)}$ and $a_1^{(v)}$, the difference in duration of the horizontal and of the vertical motion can be studied. For very low frequencies, $a_1^{(h)} > a_1^{(v)}$, but this result is not reliable due to the small number of data points used. For intermediate frequencies (0·21–4·2 Hz), the longer duration of the vertical component can be explained by the more prominent participation of P-waves in the vertical motion. The analysis shows that, for those frequencies, the origin of the first time interval contributing to the duration is different for the horizontal and for the vertical components. For vertical motions, the first strong pulse usually corresponds to the arrival of the P-wave, while the appearance of the first strong pulse on the horizontal component is usually delayed till the arrival of the S-wave. Thus, the vertical component has more strong motion pulses due to additional waves producing strong motion, and this results in an increased duration. At high frequencies ($f \geqslant 8{\cdot}5$ Hz), the difference between two components of motion disappears due to multiple scattering with mode conversions that occur at such frequencies in the highly inhomogeneous upper crust and in the sedimentary layers.

Figure 5 shows isolines of the duration of strong motion as obtained from equation (2) for various frequency bands. For comparison, the observed duration is shown (averaged over the intervals of Δ and M) by the shades of different density, with the denser shades representing longer duration. The empty 'boxes' correspond to the ranges of magnitudes and epicentral distances where no data are available.

It is of interest for earthquake engineering applications not only to be able to predict the expected value of the duration of strong ground motion, but also to evaluate the probability of exceedance of a given duration at a particular frequency. This probability can be estimated from the distribution functions of the observed residuals. We considered the distribution function of the quantity

$$\lambda = \frac{\mathrm{dur}_{\mathrm{obs}}}{\mathrm{dur}}$$

where $\mathrm{dur}_{\mathrm{obs}}$ is the observed duration and dur is the duration of the strong ground motion predicted by the model. We approximate the distribution function of λ by

$$q(\lambda) = \frac{1}{\eta} \frac{\lambda^n}{m + \lambda^k} \tag{4a}$$

where η is the normalizing coefficient:

$$\eta = m^{[(n+1)/k]-1} \frac{\pi}{k} \left[\sin \frac{(n+1)\pi}{k} \right]^{-1} \tag{4b}$$

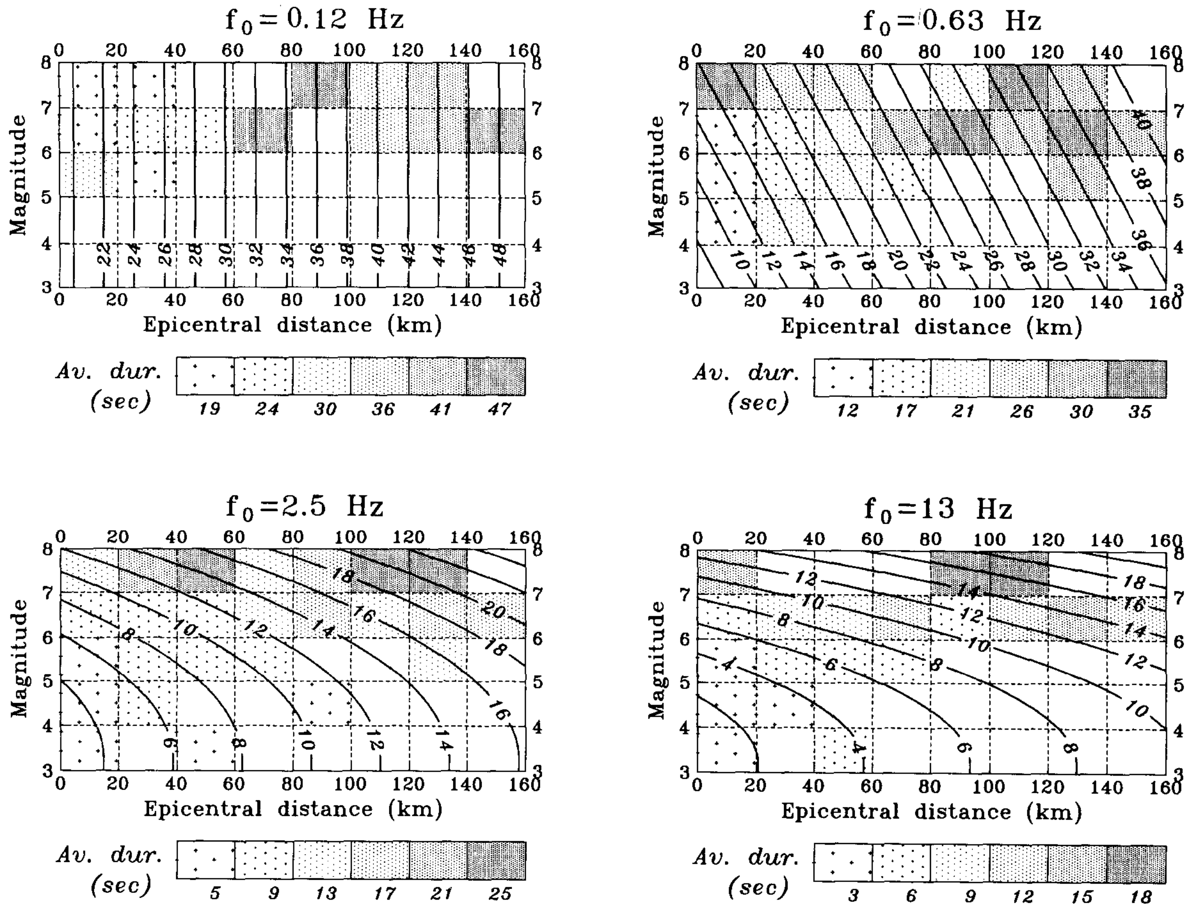

Figure 5. Isolines of the duration (in sec) of the horizontal component of strong earthquake ground motion as estimated from equation (2). The observed duration is shown averaged in the ranges of M and Δ, specified by the dashed mesh. The longer duration corresponds to a darker shade. The dependence on the epicentral distance is always linear for the displayed channels. The parabolic dependence on magnitude can be seen for high frequencies. For low frequencies, only linear dependence on magnitude can be resolved.

The coefficients m, n and k are chosen so that the cumulative distribution function $P(\lambda) = \int_0^\lambda q(\lambda)\, d\lambda$ stays close to the observed cumulative distribution function (Kolmogorov–Smirnov test). The last three columns in Table III give the 'best' values for the coefficients m, n and k for the distribution (4) for the model (2). Having the distribution function of λ, we can predict the duration of strong ground motion which will not be exceeded with any given probability at a site located at a given distance from an earthquake with a given magnitude.

Model dur = dur(M, M^2, Δ, s)

The duration of strong ground motion is influenced by the geological conditions at the site. If only parameter s is available for the site description, we model this influence by the term τ_{site} in equation (1):

$$\tau_{site} = a_{13}(f)\cdot S^{(1)} + a_{14}(f)\cdot S^{(0)} \tag{5a}$$

where[48]

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

The numbering of the coefficients was chosen in this way for consistency with our previous work[38]. The coefficient $a_{13}(f)$ shows the change in duration for intermediate ($s = 1$) sites compared with stations which are located on basement rock ($s = 2$). The second coefficient, $a_{14}(f)$, scales the change in duration for sites on sediments ($s = 0$) compared to the basement rock sites.

The results of the regression analysis of the model

$$\begin{Bmatrix} \mathrm{dur}^{(\mathrm{h})}(f) \\ \mathrm{dur}^{(\mathrm{v})}(f) \end{Bmatrix} = \begin{Bmatrix} a_1^{(\mathrm{h})}(f) \\ a_1^{(\mathrm{v})}(f) \end{Bmatrix} + a_2(f).\bar{M} + a_3(f)\cdot\bar{M}^2 + a_4(f)\cdot\Delta + a_{13}(f)\cdot S^{(1)} + a_{14}(f)\cdot S^{(0)} \tag{6}$$

are summarized in Table IV. The estimates of the coefficients m, n and k for the distribution function (4) of the relative residuals of the model (6) are also presented. The coefficients $\{a_i(f),\ i = 1\text{–}4\}$ and $M_{\min}(f)$, representing the dependence of duration on magnitude and epicentral distance, remain practically the same as their counterparts from the previously considered equation (2). Both new coefficients, $a_{13}(f)$ and $a_{14}(f)$, significantly differ from zero in the intermediate frequency range only. This can be explained[49] by visualizing a sedimentary (or soil) layer of thickness h working as a band-pass amplification filter, with high, f_1, and low, f_2, cut-off frequencies. The low cut-off is the frequency for which the corresponding quarter wavelength in sediments (or soil) coincides with the thickness h of the sediments (or soil layer). For high frequencies, the amplification effects are overshadowed by the inelastic attenuation, so f_1 depends, also, on the attenuation factor Q, typical for the sediments (or soil). The amplification effects can be explained by multiple reflections in the sedimentary basin (of course, the increase in amplitude upon entering of the soft layer also takes place). These multiple reflections are probably also responsible for the prolongation of the duration in a sedimentary valley. If the depth of sediments $h = 2$ km, shear wave velocity $\beta = 2$ km/sec and inelastic attenuation factor $Q = 100$, the above model predicts that the high cut-off frequency is $f_1 = 5$ Hz and the low cut-off frequency is $f_2 = 0{\cdot}24$ Hz. A good agreement can be found between these values of f_1 and f_2 and the frequencies that bound the range where the prolongation of duration due to the presence of a sedimentary basin ($s \neq 2$) was detected in this study.

The duration is longer on sedimentary sites than on rock sites (see coefficient a_{14}) by about 6 sec at frequency 0·63 Hz (channel #5) and by about 1 sec for channel #8 ($f_0 = 2{\cdot}5$ Hz). Excluding the high frequencies, where $a_{13}(f)$ cannot be evaluated, $a_{13}(f)$ is smaller than $a_{14}(f)$ and has larger variances. It corresponds to the duration at intermediate sites ($s = 1$, coefficient a_{13}) being shorter than the duration on sediments ($s = 0$, coefficient a_{14}). The intermediate sites ($s = 1$) do not have so 'regular' a multiple-layered sedimentary structure as the sites on sediments ($s = 0$). As a result, the multiplicity of reflections and scattering, preserving the wave energy inside a wave guide, decreases and, therefore, the duration is reduced.

Model dur = dur (M, Δ, s, s_L)

The understanding of the effects of the local site conditions on the strong ground motion amplitudes has increased significantly during the recent years.[50] Major advances have been made since the time when Kanai[51,52] studied the local soil site effects using microtremor measurements, and when Gutenberg[53] considered the effects of the geological site conditions. It is now obvious that the local soil and geological site conditions should be considered simultaneously in various scaling equations of strong motion amplitudes.[35–37,54] However, the simultaneous consideration of both the geological and the local soil conditions in the models of duration of strong ground motion was not studied previously. Theofanopulos and Watabe[22] did consider the influence of the local soil conditions. Their definition of duration of strong motion was not frequency dependent. Moreover, they analysed data from several geologically different regions (Japan, United States, Mexico and Greece) all as one data set, and did not correct their results for the regional differences. Dobry *et al.*[21] also studied duration (neglecting frequency dependence) and included the site conditions, but it is not clear whether they use geological conditions or local soil conditions.

When both the 'geological' parameter s and the 'local' soil parameter s_L are available, the site condition term τ_{site} from equation (1) can be presented as

$$a_{11}(f)\cdot S_L^{(1)} + a_{12}(f)\cdot S_L^{(2)} + a_{13}(f)\cdot S^{(1)} + a_{14}(f)\cdot S^{(0)}$$

where $S^{(1)}$ and $S^{(0)}$ are indicator variables for $s = 1$ (intermediate sites) and $s = 0$ (sites on sediments), defined by equation (5b), and $S_L^{(1)}$ and $S_L^{(2)}$ are the corresponding indicator variables for $s_L = 1$ (stiff soil sites) and $s_L = 2$ (deep soil sites). In both cases, the geological rock ($s = 2$) or the 'local soil rock' ($s_L = 0$) is chosen as

Table IV. Results of the regresssion analysis of equation (6) and coefficients in the distribution function of the residuals (equation (4)) for this model

Channel number	f_0 (Hz)	No. of data points $N(f)$	Coefficients a_i and their accuracy ('σ-interval')							M_{min}	σ_{dur} (sec)	dur_{av} (sec)	Coefficients in the distribution function of the residuals		
			$a_1^{(h)} \pm \sigma_1^{(h)}$	$a_1^{(v)} \pm \sigma_1^{(v)}$	$a_2 \pm \sigma_2$	$a_3 \pm \sigma_3$	$a_4 \pm \sigma_4$	$a_{13} \pm \sigma_{13}$	$a_{14} \pm \sigma_{14}$				m	n	k
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	2·3	3·5	12·0
2	0·12	311	19·1 ± 1·1	19·4 ± 1·6	0·0	0·0	0·191 ± 0·018	0·0	0·0		10·2	28·3	0·7	2·6	7·6
3	0·21	962	11·9 ± 0·6	13·6 ± 0·7	0·0	0·0	0·215 ± 0·012	0·0	0·0		8·1	21·4	0·4	2·9	7·1
4	0·37	1179	7·2 ± 3·4	7·3 ± 3·4	0·60 ± 0·55	0·0	0·184 ± 0·009	0·0	3·06 ± 0·51		7·7	20·5	1·2	2·4	8·1
5	0·63	1641	− 5·3 ± 2·3	− 2·9 ± 2·4	1·89 ± 0·37	0·0	0·175 ± 0·008	3·02 ± 0·85	6·02 ± 0·74		8·1	18·3	1·2	1·6	6·4
6	1·1	2171	− 6·3 ± 1·5	− 3·8 ± 1·5	2·08 ± 0·25	0·0	0·140 ± 0·006	1·39 ± 0·63	3·85 ± 0·54		7·0	15·1	1·3	1·4	6·1
7	1·7	2625	− 6·2 ± 0·9	− 3·9 ± 0·9	2·00 ± 0·15	0·0	0·120 ± 0·004	0·81 ± 0·44	2·33 ± 0·38		5·5	12·2	1·7	1·5	6·8
8	2·5	2872	5·7 ± 1·7	7·1 ± 1·7	− 2·61 ± 0·63	0·42 ± 0·06	0·082 ± 0·003	0·0	1·30 ± 0·16	3·11	3·7	8·9	1·7	1·6	6·7
9	4·2	2439	7·8 ± 1·5	9·0 ± 1·5	− 3·86 ± 0·55	0·57 ± 0·05	0·070 ± 0·003	0·0	1·14 ± 0·14	3·39	3·2	7·4	2·5	1·4	6·9
10	7·2	2351	9·3 ± 1·1	9·9 ± 1·1	− 4·67 ± 0·43	0·66 ± 0·04	0·063 ± 0·003	0·0	0·49 ± 0·12	3·54	2·6	6·3	1·9	1·6	6·7
11	13	1488	6·1 ± 1·1	6·2 ± 1·1	− 3·41 ± 0·43	0·54 ± 0·04	0·054 ± 0·003	0·0	0·38 ± 0·11	3·16	2·0	5·1	2·9	1·6	7·5
12	21	683	11·6 ± 2·3	11·7 ± 2·3	− 5·43 ± 0·91	0·70 ± 0·09	0·056 ± 0·007	0·0	0·42 ± 0·15	3·88	1·8	4·4	6·3	1·3	8·1
		Corresponding parameters	1 horiz	1 vert	M	M^2	Δ	$S^{(1)}$	$S^{(0)}$						

a reference. However, a substantial reduction in the number of data points available (because of the lack of information about s_L for many sites) causes instability of the regression analysis. Thus, we reduced the number of model coefficients by (1) considering parameter s as a quantitative 'continuous' variable (this is equivalent to the assumption that $a_{14}(f) = 2a_{13}(f)$, which is not far from being correct, see Table IV), and (2) disregarding the quadratic term in τ_0. The results of the regression analysis of the model

$$\begin{Bmatrix} \mathrm{dur}^{(h)}(f) \\ \mathrm{dur}^{(v)}(f) \end{Bmatrix} = \max\left[\left(\begin{Bmatrix} a_1^{(h)}(f) \\ a_1^{(v)}(f) \end{Bmatrix} + a_2(f)\cdot M\right), 1\right]$$
$$+ a_4(f)\cdot\Delta + a_{15}(f)\cdot(2-s) + a_{11}\cdot(f)S_L^{(1)} + a_{12}(f)\cdot S_L^{(2)} \qquad (7)$$

are shown in Table V and Figure 6. The reason for considering the term $a_{15}(f)\cdot(2-s)$ instead of $a_{15}(f)\cdot s$ is that we prefer to have basement rock as a reference and to deal with positive a_{15} if the duration on sediments is longer than on rock sites. The coefficient $a_4(f)$, scaling the influence of the epicentral distance Δ, is similar to the previous models. The coefficients $a_1(f)$ and $a_2(f)$ have a different meaning now due to a linear approximation of $\tau_0 = \tau_0(M)$.

The coefficient $a_{15}(f)$, showing the influence of the geological site conditions, now plays the role of both $a_{13}(f)$ and $a_{14}(f)$ from equation (6). For the low frequency ($f_0 = 0{\cdot}37$ Hz), the duration of motion on sediments ($s = 0$) is about 4 sec longer than on rock sites, when predicted by equation (7). The previous model, equation (6), gives about 6 sec of prolongation for the same conditions. As for the 'soil' coefficients, $a_{12}(f) \geqslant a_{11}(f) \geqslant 0$, which shows that the duration of strong ground motion is longer at the stations located on deep than on stiff soils. The duration is the shortest at the 'rock' sites (with all other factors kept constant).

The range of frequencies, where the effect of the local soils on the duration is noticeable, is about 0·63–21 Hz. The corresponding parameters of the layer of soft soil on a stiff half-space, which would produce the effect of a band-pass filter, could be the following:[49] depth of the local soft soil 50 m, shear wave velocity in the soil 100 m/sec and inelastic attenuation factor $Q = 100$. In this case, the low cut-off frequency, f_2, is about 0·5 Hz. The lower frequency waves are too long to 'notice' the existence of a soil layer and to be disturbed by it. The high cut-off, predicted by the attenuation model, is $f_1 = 25$ Hz. The high inelastic attenuation overshadows any (positive) amplification or prolongation effects possibly produced by multiple scattering in the soil layer at frequencies $f > f_1$. The range $f_1 > f > f_2$, i.e. $f \approx 0{\cdot}5$–25 Hz, obtained from the 'band-pass model' for amplification,[49] is similar to the frequency band where the presence of soft local soils prolongs the duration of strong ground motion. The range of frequencies, where the influence of the geological conditions on the duration is significant, is shifted towards low frequencies. This occurs because the characteristic depth of sediments is substantially larger than the typical depth of a soil layer.

INFLUENCE OF THE GEOMETRY OF THE SEDIMENTARY BASIN

It is sometimes feasible to use a better description of the geology around the recording sites than just lumping all sites into $s = 0$, 1 or 2. Using the geological maps, Smith's[47] map and other sources of information, we

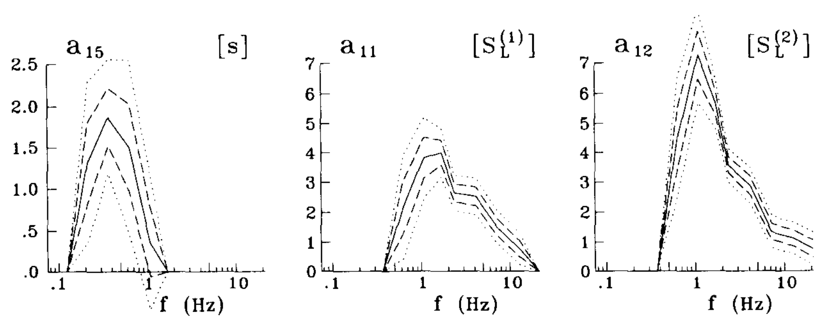

Figure 6. The coefficients $a_{15}(f)$, $a_{11}(f)$ and $a_{12}(f)$ in equation (7) plotted versus the central frequency of the channels (solid lines). The coefficients are bounded by their 'σ-intervals' (dashed lines) and by their estimated 95 per cent confidence intervals (dotted lines)

Table V. Results of the regresssion analysis of equation (7) and coefficients in the distribution function of the residuals (equation (4)) for this model

			Coefficients a_i and their accuracy ('σ-interval')									Coefficients in the distribution function of the residuals		
Channel number	f_0 (Hz)	No. of data points $N(f)$	$a_1^{(h)} \pm \sigma_1^{(h)}$	$a_1^{(v)} \pm \sigma_1^{(v)}$	$a_2 \pm \sigma_2$	$a_4 \pm \sigma_4$	$a_{15} \pm \sigma_{15}$	$a_{11} \pm \sigma_{11}$	$a_{12} \pm \sigma_{12}$	σ_{dur} (sec)	dur_{av} (sec)	m	n	k
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	2·3	3·5	12·0
2	0·12	311	19·1 ± 1·1	19·4 ± 1·6	0·0	0·191 ± 0·018	0·0	0·0	0·0	10·2	28·3	0·7	2·6	7·6
3	0·21	850	9·5 ± 1·0	11·3 ± 1·0	0·0	0·204 ± 0·012	1·32 ± 0·49	0·0	0·0	8·2	20·7	0·4	3·0	7·5
4	0·37	1179	10·0 ± 0·7	10·2 ± 0·8	0·0	0·187 ± 0·009	1·87 ± 0·35	0·0	0·0	7·7	20·5	1·3	2·3	7·9
5	0·63	1139	4·6 ± 0·7	6·9 ± 0·8	0·0	0·213 ± 0·009	1·50 ± 0·53	2·17 ± 0·89	4·47 ± 1·01	7·7	19·0	1·9	1·6	7·0
6	1·1	1376	2·9 ± 0·6	5·8 ± 0·6	0·0	0·184 ± 0·007	0·36 ± 0·42	3·83 ± 0·70	7·26 ± 0·80	7·0	16·7	2·6	1·3	6·9
7	1·7	1555	0·2 ± 1·0	2·6 ± 1·0	0·40 ± 0·15	0·156 ± 0·005	0·0	4·01 ± 0·43	5·70 ± 0·42	5·6	14·0	2·1	1·7	7·4
8	2·5	1522	− 9·2 ± 1·0	− 7·7 ± 1·1	1·97 ± 0·17	0·106 ± 0·004	0·0	2·64 ± 0·30	3·57 ± 0·29	3·9	10·3	1·9	1·8	7·3
9	4·2	1134	− 10·0 ± 1·1	− 8·8 ± 1·1	2·17 ± 0·19	0·097 ± 0·004	0·0	2·52 ± 0·31	2·87 ± 0·31	3·7	9·3	2·3	1·7	7·5
10	7·2	1070	− 11·5 ± 0·9	− 11·0 ± 0·9	2·62 ± 0·16	0·076 ± 0·004	0·0	1·51 ± 0·28	1·33 ± 0·27	3·1	8·4	1·7	2·0	7·5
11	13	616	− 10·6 ± 1·0	− 10·8 ± 1·0	2·56 ± 0·18	0·057 ± 0·006	0·0	0·77 ± 0·28	1·12 ± 0·27	2·5	7·2	3·8	2·0	9·2
12	21	273	− 9·9 ± 1·5	− 10·0 ± 1·5	2·39 ± 0·27	0·060 ± 0·011	0·0	0·0	0·75 ± 0·29	2·4	6·5	6·3	1·6	9·3
			1 horiz	1 vert	M	Δ	s	$S_L^{(1)}$	$S_L^{(2)}$					
			Corresponding parameters											

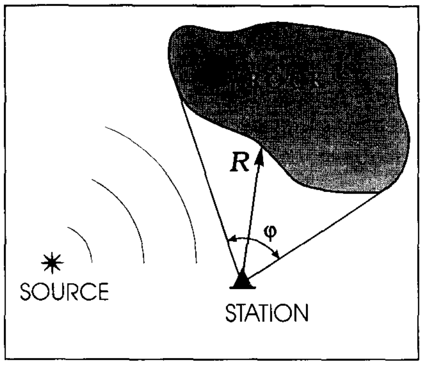

Figure 7. Definition of the parameters describing the geometry of the alluvial basin in the horizontal plane. Waves emitted by the source partially reflect from the boundaries sediments–rock, and some secondary (reflected) energy is observed at the station. The angle subtended at the station by the surface of the rocks capable of producing reflections from a particular source in the direction of the station is called φ; the distance from the station to these rocks is called R

described the position of the stations located in alluvial valleys using three parameters: (1) depth of sediments under the station, h, (2) angle (in the horizontal plane) subtended at the station by the basement rocks appearing on the surface and capable of producing reflections of seismic waves from the source in the direction of the station, φ, and (3) distance from the station to these rocks, R. The last two parameters are illustrated in Figure 7. Our data are consistent[38] with the following representation of the site dependent term τ_{site}:

$$\tau_{\text{site}} = a_5(f)\cdot h + a_6(f)\cdot R + a_7(f)\cdot hR + a_8(f)\cdot R^2 + a_9(f)\cdot h^2 + a_{10}(f)\cdot \varphi \tag{8}$$

where the above quantity is included in the model only if it is positive. The regression analysis of the model with $\tau_0 + \tau_\Delta$ as in equation (6) and τ_{site} from equation (8) gives a_1, a_2, a_3 and a_4 very similar to those obtained from equation (6). The prolongation of duration on sediments as described by the above τ_{site} is well defined in the intermediate frequency range only, similar to the range which we found for $\tau_{\text{site}} = a_{13}(f)\cdot S^{(1)} + a_{14}(f)\cdot S^{(0)}$, but horizontal and vertical components have different coefficients a_5–a_{10} (Figure 8). One explanation of the results shown in Figure 8 is as follows. We assume that the well-defined boundary of the sedimentary valley (like the boundary between alluvium and granites) generates secondary waves by reflecting the direct waves coming from the source (Figure 7). If the station is located very close to the boundary of the valley, the direct and reflected strong motion waves overlap, causing just a small increase in the duration of strong motion. Moving the observation site away from the boundary increases separation of the direct and reflected pulses, which results in increase in duration. Thus, at frequency $f_0 = 0{\cdot}63$ Hz, a station located at about 30–40 km from the edge of a valley and on 2 km of alluvium can show up to 7 sec of additional duration of strong motion on the horizontal component (relative to a rock site). When the reflecting rocks are located too far from the station, the secondary (reflected) waves are weakened by attenuation and cannot be observed. This explains the gradual diminishing of the additional duration when R and h are large. As for the angle of effective reflections, φ, the greater this angle, the more the reflected energy observed at the station, and the longer the additional duration. At the frequencies where the influence of the geometry of the alluvial valley is most significant (0·5–2 Hz), an increase of the angle φ by 100° prolongs duration by 2 sec (Figure 8). It is remarkable that almost all the data points (pairs R–h) used in our analysis (asterisks in Figure 8) appear to give positive values for $a_5\cdot h + a_6\cdot R + a_7\cdot hR + a_8\cdot R^2 + a_9\cdot h^2$. Hence, adding the contribution from $a_{10}(f)\cdot\varphi$, an absolute majority of the data points give positive τ_{site} (equation (8)). This provides additional support for our choice of the term τ_{site} in the form of equation (8).

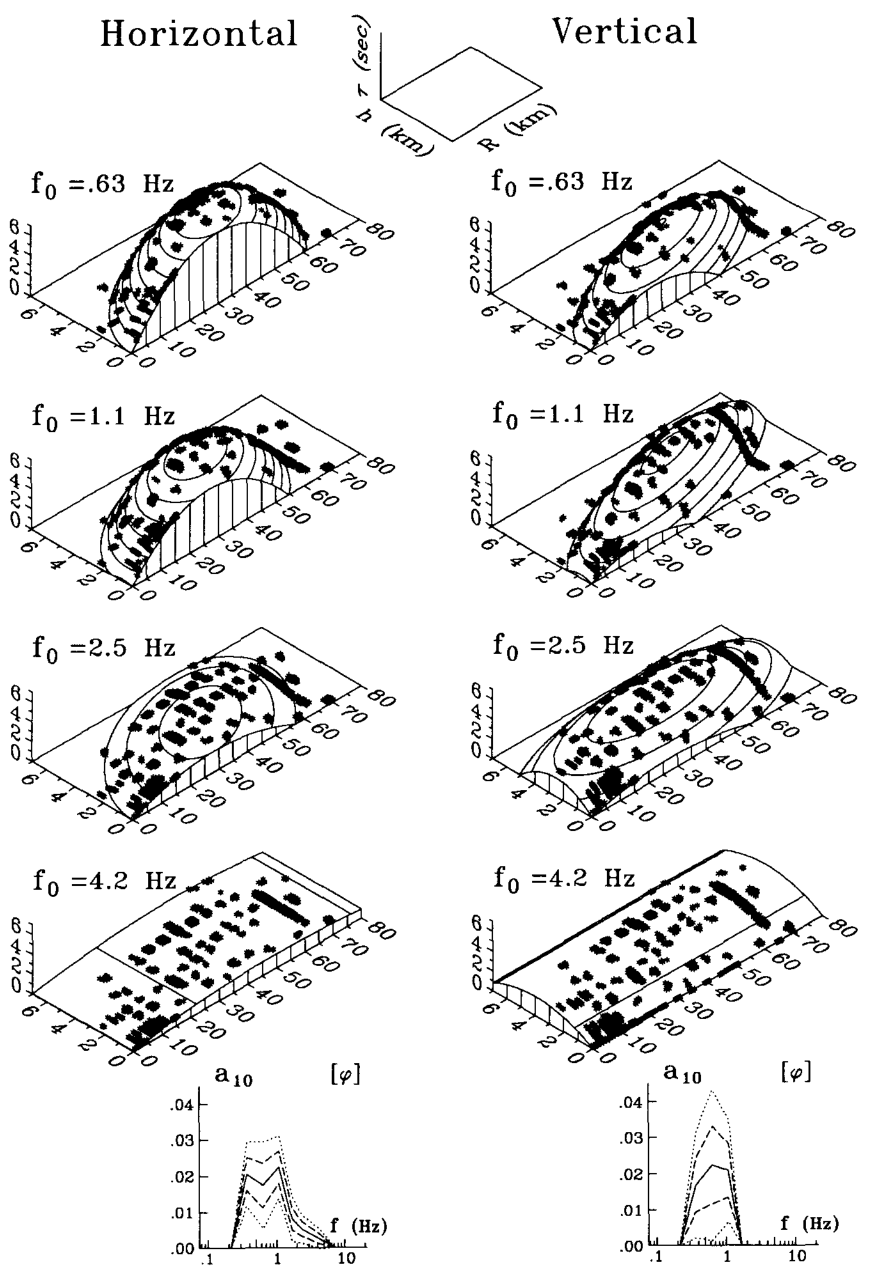

Figure 8. Additional duration as a function of the depth of sediments under the recording station, h, and the horizontal characteristic dimension of the sedimentary valley (distance from the station to the rocks), R, is shown (as obtained from the model with τ_{site} as in equation (8) for horizontal and vertical components) of motion at several frequency bands. The isolines on the three-dimensional surface are drawn with 1 sec increments, starting from the 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 contribution from the angle φ (measured in degrees) is shown at the bottom, where the regression coefficient a_{10} in the term τ_{site} (equation (8)) is plotted versus the central frequency of the channels (solid lines), with dashed lines showing its 'σ-interval' and dotted lines showing its 95 per cent confidence interval

DISCUSSION AND CONCLUSIONS

The results of the preceding analysis show a good stability of the estimates of the terms $\tau_0 + \tau_\Delta$ for several types of the site condition term τ_{site}. A comparison of the estimates of τ_{site} using equations (6) and (7) shows that the high frequency contribution to τ_{site} can be attributed (incorrectly, due to coupling of the parameters s and s_L) to the influence of the geology at a site, while in reality it is the influence of smaller scale factors, i.e. local soil site conditions. The results of the analysis of equation (7) explicitly show the difference in the frequency ranges of the predominant influence of geological and local soil conditions. This emphasizes the importance of the simultaneous consideration of the site description on several scales. Unfortunately, we have enough data to describe the sites on two scales only: a geological scale (several kilometres) and a local geomechanical scale (several tens of metres), leaving a gap in between. Gathering more complete information about site conditions is essential for the future improvement of our understanding of the strong ground motion characteristics and the influence of the local conditions on these characteristics. One possible way of describing a site more completely is presented in this paper ('influence of the geometry of the sedimentary basin') by considering the edges of the basin as possible reflectors of the seismic energy back into the valley. This approach is particularly useful when the emission of the seismic energy almost entirely takes place in sediments (and not in the basement rocks beneath the sediments; e.g. Imperial Valley, 1940 and 1979 earthquakes[55–58]) or when a significant portion of this energy initially penetrates into the valley so that secondary reflections from the valley's edges still carry enough energy to produce noticeable strong motion. The distribution of typical locations of the earthquake sources and of the recording stations with respect to sedimentary valleys is shown in Figure 9. This distribution shows that, in addition to the 'reflection distance' R considered in this paper, one may study the influence on duration (and on other strong motion parameters)

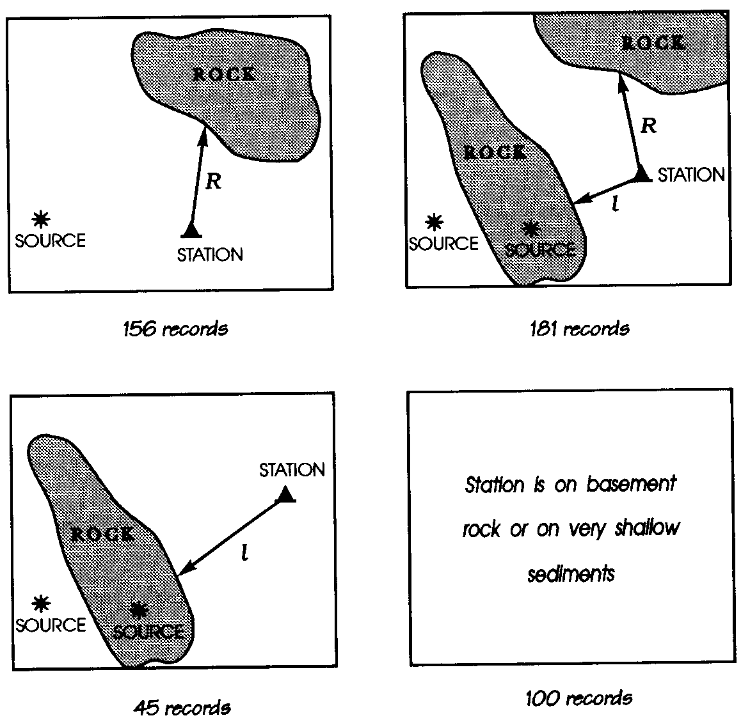

Figure 9. Distribution of records in our database with respect to the mutual location of the earthquake source, recording station and the sedimentary valleys in the area of strong ground shaking. R is the 'reflection distance' defined in Figure 7. l is the distance from the station to the edge of the valley where the surface waves are likely to be generated by the body waves entering the sedimentary basin. Cases where only R (top left), both R and l (top right), only l (bottom left) and none of these distances (bottom right) can be defined are shown

of the distance from the edge of the valley (where the surface waves are generated by the body waves entering the sedimentary basin) to the station, l. This is only one example of the possible future developments of the models introduced in this paper.

The results of this work can be used to estimate the duration of strong ground motion produced by future earthquakes, when the parameters of the shock and the properties of the site are known or can be estimated. The complete regression analysis was performed for three models. If no other information, except the magnitude and the epicentral distance, is available, the model (2) should be used. If the geological parameter s is known, equation (6) should be considered, and if the local soil conditions are also known, the most 'complete' equation (7) should be used for the estimation of duration. The residuals of the model equations were studied and the distribution function of these was also proposed.

Our regression equations are useful for the construction of realistic synthetic accelerograms, as the duration of strong ground motion is one of the essential parameters necessary for the generation of artificial strong ground motion.[12–15] Other future applications of our results are related to the earthquake hazard assessment, which can also be characterized by probabilistic measures of the duration of the strong ground motion. Using a technique similar to that of the uniform risk spectrum approach,[59,60] the probability of exceedance of any given duration at any frequency at a given location can be estimated. We expect that such results will be useful in future studies of liquefaction and of lateral mobility of soils.

We recommend against using our regression models (with the coefficients we obtained) in a region different from the one where the data were collected. It might (and it will) happen that different geological environments can change the prevailing earthquake mechanism, the distribution of hypocentral depths of the sources, the representative velocities and the attenuation factors, and other possible conditions that influence the values of the regression coefficients. Another restriction in the application of our models comes from the 'completeness' of the database. It covers only a restricted range of earthquake magnitudes and distances to the epicentre, for example. We suggest that only predictions coming from interpolation, not extrapolation, may be acceptable.

To obtain models which can be useful in other regions, similar analysis should be performed using the local database and the regression equations analogous to those presented here. The resulting regression coefficients will differ from those presented in this paper, reflecting the differences in the earthquake triggering mechanism and wave propagation conditions.

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