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THE PREDICTION OF STRONG-MOTION DURATION FOR ENGINEERING DESIGN

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ABSTRACT

Some twenty definitions of strong-motion duration are reviewed. A new definition is presented for the duration of earthquake strong-motion taking account of the seismic energy content of the record. The duration is the interval over which a significant amount of seismic energy is carried by the time-history, commencing at the time at which the Arias intensity reaches a specified absolute level. The end of the duration is defined by the time at which the additional seismic energy carried in a specified time interval is a small fraction of the energy already accumulated. This duration differs from previous definitions based on the build up of seismic energy because it is related to absolute rather than relative levels of seismic motion, so the duration is not defined for "weak" accelerograms.

The dependence of this effective duration on magnitude and distance is explored by determining its value for a large number of accelerograms recorded on rock. The results suggest that it is not possible to find a simple correlation of the duration with magnitude and distance due to source effects and that the prediction of strong-motion duration in the near-field needs to include the fault rupture process.

KEYWORDS

Strong-motion duration; bracketed duration; uniform duration; significant duration; effective duration; Arias intensity; earthquake accelerograms; rock sites; near-field motions.

INTRODUCTION

It has long been recognised that the maximum amplitude of ground acceleration is a poor indicator of the destructive potential of seismic motions, which is more closely related to energy content of the earthquake shaking at a site. The duration of the strong shaking, which is related to the number of cycles of earthquake motion, is an important parameter in determining the response of structures and their foundations. The duration of the shaking has been shown to have a significant effect in some cases on the inelastic deformational and energy dissipation demands of structures (Mahin, 1980). On the geotechnical engineering side, the seismic response of soils is strongly dependent upon the number of cycles of loading, especially in terms of the pore pressure build up and liquefaction potential. This is clearly illustrated by the curves prepared by Ambraseys (1988) for the evaluation of liquefaction potential. For a given soil, the ground accelerations associated with the maximum distance from the earthquake at which liquefaction could be expected decreases with increasing magnitude, reflecting the influence of the longer duration of shaking.

The objective of this study is to develop predictive equations for strong-motion for two specific purposes. The first is for the assessment of liquefaction potential, since the expected duration of strong shaking, in conjunction with the expected maximum amplitude of motion, could provide a convenient criterion for a preliminary assessment. The second purpose is related to the development of techniques for selecting and scaling real strong-motion records for use in earthquake-resistant design. Predictive equations for strong-motion duration enable this parameter to be constrained in the selection. The equations can also be incorporated into multi-parameter probabilistic seismic hazard assessments, as has been done for Greece (Papazachos *et al.*, 1992), in order to provide tighter control over the definition of hazard-consistent magnitude-distance pairs (Ishikawa and Kameda, 1988; McGuire, 1995). Although the main focus is the selection of real accelerograms, the results will be equally applicable to the generation of synthetic records.

The first stage in the development of equations to predict strong-motion duration is establish an appropriate definition for the strong-motion duration. The existing definitions of duration are reviewed and a new definition is proposed. The relationship of this new duration to magnitude and distance is investigated in order to verify the physical meaning of the definition and to select the form of the predictive model.

DEFINITIONS OF STRONG-MOTION DURATION

A large number of different proposals have been advanced to define the duration of strong shaking from earthquake accelerograms, which have been thoroughly reviewed elsewhere (Trifunac and Novikova, 1995; Bommer and Martinez, 1996). Some of these definitions of duration are based on structural response and are therefore related to specific structural characteristics (Perez, 1977; Zahrah and Hall, 1984; Xie and Zhang, 1988; Mohraz and Peng, 1989). To establish relations which can be used in general seismic hazard evaluations, these structure-dependent definitions are not suitable. All the definitions of duration based on characteristics of the recorded ground motion can be broadly categorised into three different types.

The simplest definition is the "bracketed duration", which is the total time elapsed between the first and last excursion of a given level of acceleration. The first use of this definition was by Ambraseys and Sarma (1967), who chose a threshold level of 0.03g. A very slight variation of the definition was applied by Page *et al.* (1972) who used the interval between the first and last peaks of acceleration with amplitudes greater than or equal to 0.05g. Bolt (1973) gave the name of bracketed duration to the definition and used the interval between the first and last excursions greater than 0.05g, but only at particular frequencies, applying narrow pass-band filters to the accelerograms before calculating the durations. McGuire and Barnhard (1979) used the concept of a bracketed duration with thresholds of 0.1, 0.15 and 0.2g. They also introduced the concept of "fractional duration" in which the threshold was defined not by an absolute acceleration but as a proportion (0.5, 0.67 or 0.75) of the peak. This same concept was employed by Kawashima and Aizawa (1989) who used thresholds from 0.1 to 0.9 of the peak and referred to the definition as "normalized duration".

The simplicity of the bracketed duration makes it an attractive definition, but it has a number of serious disadvantages, one of these being that for several accelerograms the measured duration is highly sensitive to small changes in the threshold level (Pagratis, 1995). Moreover, the definition completely ignores the nature of the record during the strong part of the shaking and even when using an absolute threshold level the same duration could be given for two accelerograms with very different energy contents. An improvement on this definition, which considers characteristics of the entire record, is the "uniform duration"; this is the sum of the time intervals during which the acceleration level exceeds a specified threshold. Bolt (1973) first proposed this definition, using thresholds of 0.05g and 0.1g. The definition has the advantage that the duration does not vary abruptly with small changes in the threshold level, but at the same time it does not define the continuous time window during which the motion can be considered to be strong. Sarma and Casey (1990) found that the uniform duration is exponentially related to the threshold level and used this to define a new duration. The duration of Sarma and Casey is calculated in a way that considers the energy in the record, but only in a relative sense, considering the levels of acceleration below which 10% and 95% of the energy are contained. The extrapolation used to calculate the duration makes its physical interpretation unclear.

A large number of definitions for strong-motion duration have been put forward that are based on the accumulation of seismic energy in the accelerogram, which are classified as "significant duration". The significant duration is usually based on the integral of the square of the acceleration, but some studies have also used the square of the velocity and the displacement (Trifunac and Brady, 1975). In view of the uncertainty associated with the displacement time-histories obtained by double integration of accelerograms, its use is not considered appropriate, and to some extent the same is true of velocity. Many of the available definitions use the build up of the Arias intensity, I_A, which is defined as:

$$I_A = \frac{\pi}{2g} \int_0^T a^2(t)\,dt \,, \qquad (1)$$

where a(t) is the accelerogram of total duration T; I_A is a measure of the amount of energy that goes into the production of damage (Arias, 1970). A curve showing the increase of I_A as a function of time is usually referred to as a Husid plot (Husid *et al.*, 1969). The Husid plot for a horizontal accelerogram normally consists of an initial portion of shallow gradient associated with the arrival of P waves and a steeper central section which corresponds to the main energy input through S waves and sometimes surface waves. The final portion of the plot is generally of relatively shallow gradient and it is associated with indirect body wave arrivals, surface waves and energy trapped by topographical features and sediment layers. The gradient of any portion of the Husid plot is square of the root-mean-square (rms) acceleration.

The simplest measurements of significant duration are based on the interval over which a specified portion of I_A is achieved: Husid *et al.* (1969) used the 95% interval, Donovan (1972) used the interval from 0 to 90%, and Trifunac and Brady (1975) modified this to the interval from 5% to 95%, which was also used by Dobry *et al.* (1978). McGuire and Barnhard (1979) examined the use of other percentages of the Arias intensity. The definition presented by Trifunac and Westermo (1982) and by Novikova and Trifunac (1994) for duration at particular frequencies, is a hybrid of this significant duration and the uniform duration, being the smallest sum of the intervals over which 90% of the total Arias intensity is generated.

Other studies have used features of the shape of the Husid plot to define the significant duration. Housner (1975) plotted the square root of I_A against time and defined the duration as the interval over which the steepest part of the curve could be approximated by a straight line. McCann and Shah (1979) and McCann and Boore (1983) used plots of the cumulative rms acceleration of the accelerogram and its reversal to define the start and end of the strong duration from the points beyond which this quantity steadily decays. Vanmarcke and Lai (1980) defined the duration as the interval during which there was a specified probability of exceedance of the ratio of peak to rms acceleration.

Shahabi and Mostaghel (1984) defined the duration as the time from the start of the accelerogram after which the area below the Husid plot is equal to the area that would have been obtained had the Arias intensity risen linearly to its final maximum value in the same interval. Theofanopoulos and Drakopoulos (1986) defined the interval over which the increase in the Arias intensity is rapid relative to the average growth up to that time. Zhou and Katayama (1985) defined the duration as one standard deviation either side of the time corresponding to the centre of gravity of the Arias intensity and Theofanopulos and Watabe (1989) used a similar definition based on the centre of gravity of the increments of Arias intensity.

All of the definitions of significant duration define the length of time over which the ground motion is strong, but only in a relative sense. Novikova and Trifunac (1994) argue that such relative definitions are useful since combined with information about the Fourier spectral amplitudes they provide a fairly complete description of the ground motion. This is true when the definition of duration is frequency-dependent and is useful when the final objective is to generate synthetic time histories, but not necessarily for the applications of interest to this study. Some researchers reject the absolute definitions of bracketed duration because if the maximum acceleration is below the threshold level the duration is zero (Zhou and Katayama, 1985). The authors do not see this as a limitation since the aim is to obtain a definition of the duration of "strong" motion.

EFFECTIVE DURATION

The new definition for effective duration presented in this paper is based on the significant duration concept, since this is related to the energy in the record. However, unlike previous definitions, the duration is related to absolute threshold levels. The use of absolute thresholds avoids the problem of obtaining predictive relationships which estimate durations that have no engineering significance: Theofanopolus and Watabe (1989) point out that their equations predict durations for earthquakes with magnitude less than 6 at distances greater than 100 km which are meaningless.

The first step is to select an appropriate threshold level of I_A from which the duration would be measured, which is named I_0. A value of 0.05 m/sec is chosen as suitable from the inspection of a large number of accelerograms, covering a wide range of values of magnitude and distance likely to be of engineering interest. However, since this value of I_0 represents an appreciable level of seismic energy, the beginning of the strong-motion interval, t_0, is taken at some time Δt before I_A reaches 0.05 m/sec as shown in Fig. 1. In this first evaluation of the new definition, 1.0 second is selected as a suitable value of Δt. Clearly, if the Arias intensity of an accelerogram never reaches I_0, the duration is zero. Furthermore, if the maximum value of I_A that the record attains is less than twice I_0, it is not logical to define an interval of strong-motion shaking that commences half way through the total accumulation of seismic energy. Therefore, if the Arias intensity of either component of an accelerogram is less than or equal to $2I_0$ (0.10 m/sec), the duration is taken to be zero.

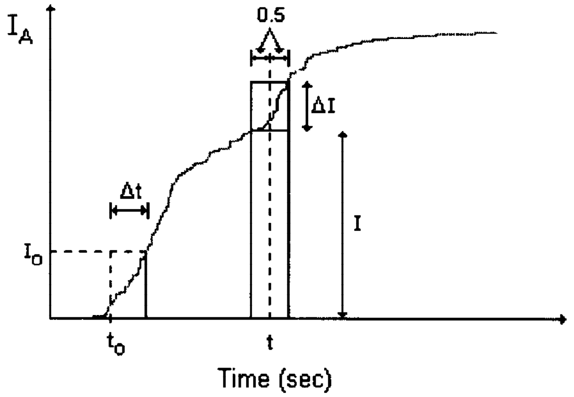

Fig. 1. Definition of effective duration of strong-motion.

The next step is to define the time t_f at which the strong-motion interval finishes. Two alternatives were considered, based on the incremental build up of I_A in a moving time window of 1 second, as shown in Fig. 1. The first option is to define t_f as the time at which the average absolute increase of I_A in a time interval of 1 second, equal to ΔI, drops to a certain level. However, for the strongest records this level of energy could be provided by indirect wave arrivals and other paths effects. In order to define a strong-motion interval that is more likely to be related to the source rupture, a relative definition was used, based on the ratio of ΔI to I. The time t_f is defined as the point at which the ratio reaches 0.01, which represents the time at which the rate of increase of I_A per second is approximately equal to 0.5% of the value already attained. The effective duration is then defined as the difference between t_0 and t_f.

EFFECTIVE DURATIONS AT ROCK SITES

In the simplest formulation, the duration of the strong shaking at a site due to an earthquake will be a function of the duration of source rupture, effects of the travel path such as separation of waves with different propagation velocities and effects due to the site, particularly multiple wave reflections within soft soil layers. In order to isolate the influence of the site conditions, a data set of 225 records recorded at rock sites was selected on the basis of site classifications given by Ambraseys *et al.* (1996) for European records and Abrahamson and Litehiser (1989) for other areas of the world. Records from outside Europe recorded after 1986 were selected from the data set used by Ambraseys and Srbulov (1994). The distances and magnitudes are taken directly from each reference, except that for non-European earthquakes preference was given to magnitudes presented by Ambraseys and Srbulov (1994), resulting in most of the values used being uniformly re-calculated M_s, ranging from 4.0 to 8.1. The duration was calculated for both horizontal components of each accelerogram and it was found that according to the criterion established above the value is non-zero for 56 records. All the data points were plotted as a function of magnitude and logarithm of distance and a line drawn through the data which is approximately an upper bound for those accelerograms that do have a duration, the equation of which is:

$$\log(d) = 0.22M_s + 0.13 , \qquad (2)$$

where d is distance in kilometres, valid for magnitudes greater than 4.5 since no durations were obtained from smaller earthquakes. The magnitude-distance pairs described by eq. (2) correspond to a peak horizontal acceleration of 0.07g according to the attenuation equations of Ambraseys and Bommer (1991).

The calculated values of effective duration are presented in the Appendix, together with the maximum value of I_A reached by each component record and the bracketed duration for a threshold of 0.05g. The longest bracketed durations, in excess of 40 seconds, are from the Irpinia (Italy) earthquake of 1980 which was clearly identified as a multiple event with the last sub-event commencing 38 seconds after the initiation of rupture (Westaway and Jackson, 1987). The effective durations of the Irpinia records, which correspond to the largest sub-event, are of the order of 10 seconds.

In order to explore the relationship between the effective duration and magnitude, the effective duration of both components of accelerograms recorded at source-site distances of less than 10 km are plotted against magnitude in Fig. 2. A clear exponential dependence of the effective duration on magnitude can be observed, which is expected. The only outstanding deviation from the general trend is the accelerogram from the 1989 Loma Prieta earthquake, but the fault rupture associated with this earthquake was clearly bi-lateral (Wald *et al.*, 1991), so for the same rupture velocity the duration would be expected to be half as much as for uni-lateral rupture. Since all but one of the earthquakes with magnitude greater than or equal to 6 in Fig. 2 have thrust mechanisms, no correlation with the fault type can be found from this data set.

DISCUSSION

The preliminary results suggest that the effective duration is a useful definition, with real physical significance. Nonetheless, the correlation of this duration with seismic and geophysical parameters requires consideration of the rupture history. This investigation is presented in a full report, together with an examination of the sensitivity of the duration to changes in the criteria used to locate t_o and t_f (Bommer and Martinez, 1996). The use of an absolute value of ΔI to control t_f is also explored.

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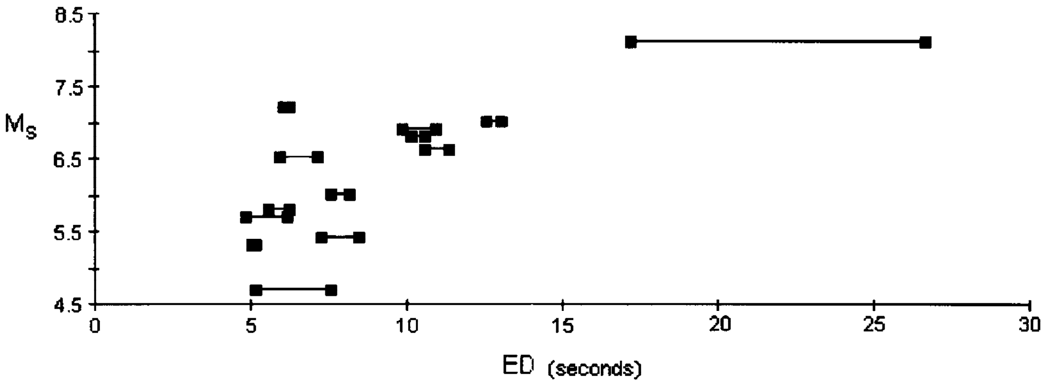

Fig. 2. Effective durations of accelerograms recorded on rock at source-site distances of less than 10 km.

NOTES ON APPENDIX

Ctry is the country. F is the dominant fault mechanism: S-strike-slip, N-normal, T-thrust. d is the source-site distance in kilometres. The final eight columns give the peak acceleration (a_{max}) in g, the maximum Arias intensity (I_A) in m/sec, the bracketed duration (BD) using a 0.05g threshold and the effective duration (ED), both in seconds, for the longitudinal and transverse components of each accelerogram.

REFERENCES

Abrahamson, N.A. and J.J. Litehiser (1989). Attenuation of vertical peak acceleration. *Bull. Seis. Soc. Am.*, **79**, 549-580.

Ambraseys, N.N. (1988). Engineering seismology. *Earthquake Eng. Struct. Dyn.*, **17**, 1-105.

Ambraseys, N.N. and J.J. Bommer (1991). The attenuation of ground accelerations in Europe. *Earthquake Eng. Struct. Dyn.*, **17**, 1-105.

Ambraseys, N.N. and S.K. Sarma (1967). Response of earth dams to strong earthquakes. *Geotechnique*, **17**, 181-283.

Ambraseys, N.N., K.A. Simpson and J.J. Bommer (1996). The prediction of horizontal response spectra in Europe. *Earthquake Eng. Struct. Dyn.*, **25**, (in press).

Ambraseys, N.N. and M. Srbulov (1994). Attenuation of earthquake-induced ground displacements. *Earthquake Eng. Struct. Dyn.*, **23**, 467-487.

Arias, A. (1970). A measure of earthquake intensity. In: *Seismic design for nuclear power plants* (R.J. Hansen, Ed.), MIT Press, 438-483.

Bolt, B.A. (1973). Duration of strong ground motion. *Proc. Fifth World Conf. Earthquake Engineering*, **1**, 1304-1315.

Bommer, J.J. and A. Martinez (1996). The prediction of earthquake strong-motion duration for engineering design. *ESEE Research Report No.96/1*, Imperial College, London.

Dobry, R., I.M. Idriss and E. Ng (1978). Duration characteristics of horizontal components of strong-motion earthquake records. *Bull. Seis. Soc. Am.*, **68**, 1487-1520.

Donovan, N.C. (1972). Earthquake hazard for buildings. *Building Science Series*, **46**, 82-111.

Housner, G.W. (1975). Measures of the severity of ground shaking. *Proc. US Nat. Conf. Earthqu. Eng.*, 25-33.

Husid, R., H. Medina and J. Rios (1969). Analisis de terremotos norteamericanos y japoneses. *Revista del IDIEM*, **8**, 1.

Ishikawa, Y. and H. Kameda (1988). Hazard-consistent magnitude and distance for extended seismic risk analysis. *Proc. Ninth World Conf. Earthquake Eng.*, **2**, 89-94.

Kawashima, K. and K. Aizawa (1989). Bracketed and normalized durations of earthquake ground acceleration. *Earthquake Eng. Struct. Dyn.*, **18**, 1041-1051.

Mahin, S.A. (1980). Effects of duration and aftershocks on inelastic design earthquakes. *Proc. Seventh World Conf. Earthquake Eng.*, **5**, 677-680.

McCann and D.M. Boore (1983). Variability in ground motions: root mean square acceleration and peak acceleration for the 1971 San Fernando, California, earthquake. *Bull. Seis. Soc. Am.*, **73**, 615-632.

McCann and H.C. Shah (1979). Determining strong-motion duration of earthquakes. *Bull. Seis. Soc. Am.*, **69**, 1253-1265.

McGuire, R.K. (1995). Probabilistic seismic hazard analysis and design earthquakes: closing the loop. *Bull. Seis. Soc. Am.*, **75**, 1275-1284.

McGuire, R.K. and T.P. Barnhard (1979). The usefulness of ground motion duration in predicting the severity of seismic shaking. *Proc. Second U.S. Nat. Conf. Earthquake Eng.*, 713-722.

Mohraz, B. and M.-M. Peng (1989). Use of low-pass filter in determining the duration of strong ground motion. *Jrnl. Pressure Vessels and Piping Div. ASME*, **182**, 197-200.

Novikova, E.I. and M.D. Trifunac (1994). Duration of strong ground motion in terms of earthquake magnitude, epicentral distance, site conditions and site geometry. *Earthquake Eng. Struct. Dyn.*, **23**, 1023-1043.

Page, R.A., D.M. Boore, W.B. Joyner and H.W. Coulter (1972). Ground motion values for use in seismic design of the trans-Alaska pipeline system. *US Geological Survey Circular 672.*

Pagratis, D. (1995). Prediction of earthquake strong ground motion duration for engineering use. *MSc Dissertation*, Imperial College, London.

Papazachos, B.C, Ch.A. Papioannou, V.N. Margaris and N.P. Theodulidis (1992). Seismic hazard assessment in Greece based on strong motion duration. *Proc. Tenth World Conf. Earthquake Engineering*, **2**, 425-430.

Perez, V. (1977). Response time duration of selected United States strong motion earthquake records. *Proc. Sixth World Conf. Earthquake Engineering*, **1**, 923.

Sarma, S.K. and B.J. Casey (1990). Duration of strong motion in earthquakes. *Proc. Ninth Eur. Conf. Earthquake Eng.*, **10-A**, 174-183.

Shahabi, M. and N. Mostaghel (1984). Strong ground motion duration and effective cyclic acceleration. *Proc. Eighth World Conf. Earthquake Eng.*, **2**, 843-850.

Theofanopoulos, N. and J. Drakopoulos (1986). A study of strong motion duration of earthquakes in Greece. *Proc. Eighth Eur. Conf. Earthquake Eng.*, **1**, 3.2/65-3.2/72.

Theofanopulos, N.A. and M. Watabe (1989). A new definition of strong motion duration and comparison with other definitions. *Struct. Eng./Earthquake Eng.*, **6**, 111s-122s.

Trifunac, M.D. and A.G. Brady (1975). A study on the duration of strong earthquake ground motion. *Bull. Seis. Soc. Am.*, **65**, 581-626.

Trifunac, M.D. and E.I. Novikova (1995). State of the art review on strong motion duration. *Proc. Tenth Eur. Conf. Earthquake Eng.*, **1**, 131-140.

Trifunac, M.D. and B.D. Westermo (1982). Duration of strong earthquake shaking. *Soil. Dyn. Earthquake Eng.*, **1**, 117-121.

Vanmarcke, E.H. and S-S. P. Lai (1980). Strong-motion duration and rms amplitude of earthquake records. *Bull. Seis. Soc. Am.*, **70**, 1293-1307.

Wald, D.J., D.V. Helmberger and T.H. Heaton (1991). Rupture model of the 1989 Loma Prieta earthquake from the inversion of strong-motion and broadband teleseismic data. *Bull. Seis. Soc. Am.*, **81**, 1540-1572.

Westaway, R. and J. Jackson (1987). The earthquake of 23 November 1980 in Campania-Basilicata (southern Italy). *Nature*, **312**, 436-438.

Xie, L. and X. Zhang (1988). Engineering duration of strong motion and its effect on seismic damage. *Proc. Ninth World Conf. Earthquake Engineering*, **2**, 307-312.

Zahrah, T. and W.J. Hall (1984). Earthquake energy absorption in SDOF structures. *Jrnl. Struct. Eng. Div. ASCE*, **110**, ST8, 1757-1772.

Zhou, Y. and T. Katayama (1985). Effects of magnitude, epicentral distance and site conditions on the duration of strong ground motion. *Seisan Kenkyu*, **37**, 10-13.

APPENDIX: Effective durations at rock sites

Yr	Mn	Dy	Time	Ctry	F	M_s	d	Station	a_{max}	I_A	BD	ED	a_{max}	I_A	BD	ED
1966	VI	28	20:26	USA	S	6.1	11	Temblor	0.275	0.32	3.7	6.3	0.366	0.46	3.5	4.2
1970	XII	9	06:30	USA	S	5.5	15	Wrightwood	0.144	0.13	2.8	4.3	0.207	0.15	2.3	4.6
1971	II	9	06:01	USA	T	6.6	3	Pacoima Dam	1.229	8.94	34.0	10.6	1.169	8.16	33.6	11.4
							15	Lankershim Blv.	0.174	0.20	6.7	8.9	0.151	0.30	6.2	9.6
							17	Griffith Park	0.185	0.37	7.8	10.9	0.174	0.52	9.6	11.0
							19	Lake Hughes #12	0.369	0.93	14.2	8.4	0.285	0.82	14.5	6.5
							23	Lake Hughes #9	0.144	0.14	4.9	7.8	0.139	0.11	3.5	7.3
							23	Castaic Old Ridge Rt	0.329	0.71	15.0	9.3	0.274	1.00	19.7	16.6
							24	L.A. Water &Power	0.132	0.20	6.6	7.4	0.182	0.23	8.4	9.3
							25	Lake Hughes #4	0.190	0.25	7.9	9.3	0.157	0.21	5.1	9.1
							28	Santa Anita Dam	0.158	0.29	11.4	12.0	0.203	0.30	8.6	10.3
							36	Pearblossom P.P	0.098	0.15	8.0	12.7	0.135	0.26	10.3	12.5
1976	V	6	20:00	ITA	T	6.5	6	Tolmezzo 1	0.358	0.79	7.5	6.0	0.314	1.16	6.1	7.2
1976	IX	15	09:21	ITA	T	6.0	6	Tarcento	0.136	0.20	5.8	8.2	0.112	0.12	5.0	7.6
1978	VIII	13	22:45	USA	T	5.7	12	Goleta Substation	0.240	0.27	3.7	4.5	0.273	0.29	2.4	4.3
1979	IV	15	06:19	YUG	T	7.0	9	Ulcinj-2	0.183	0.62	12.9	12.6	0.228	0.74	11.3	13.1
							29	Herceg-Novenia	0.223	0.73	10.8	11.9	0.255	0.46	10.9	9.4
1979	V	24	17:23	YUG	T	6.3	19	Kotor-1	0.119	0.14	5.9	6.6	0.152	0.19	4.4	7.2
1979	VIII	6	17:05	USA	S	5.7	4	Gilroy #6	0.320	0.68	5.8	6.2	0.421	0.77	3.7	4.9
1979	IX	19	21:35	ITA	N	5.8	6	Cascia-A	0.153	0.26	11.7	5.6	0.206	0.19	4.9	6.3
1979	X	15	23:16	USA	S	6.9	24	Cerro Prieto	0.155	1.32	41.2	25.1	0.166	1.19	32.8	24.6
1980	XI	23	18:34	ITA	N	6.9	8	Bagnoli-Irpinia	0.137	0.37	41.6	11.0	0.184	0.45	42.5	9.9
							16	Sturno	0.216	1.30	44.4	14.0	0.325	1.51	43.5	11.9
							22	Bisaccia	0.096	0.28	41.4	9.9	0.082	0.23	41.2	7.1
1983	I	17	12:41	GRE	T	7.0	23	Argostoli	0.165	0.31	10.5	10.2	0.142	0.27	8.3	8.2
1983	V	2	23:42	USA	T	6.6	24	Parkfield VC 2E	0.178	0.40	10.5	8.6	0.121	0.25	4.7	7.1
							29	Slack Canyon	0.172	0.30	6.8	9.9	0.136	0.24	3.6	10.1
							32	Parkfield VC 3W	0.138	0.22	5.7	10.7	0.099	0.26	6.1	10.1
							32	Parkfield F.Z 10	0.132	0.22	10.4	8.4	0.075	0.18	7.1	7.5
							41	Parkfield GH 3W	0.123	0.16	3.9	9.4	0.138	0.16	3.5	7.7
1983	V	9	02:49	USA	T	5.1	13	Anticline Rdge. FF	0.552	0.70	5.0	3.0	0.592	0.62	2.6	3.7
							13	Anticline Rdge. Pad	0.468	0.57	5.0	3.1	0.477	0.79	3.4	3.7
							13	Palmer Avenue	0.252	0.13	1.0	3.0	0.212	0.11	1.1	4.0
							13	Oil City	0.289	0.31	2.4	3.8	0.234	0.14	3.8	4.7
1983	VII	9	07:40	USA	T	5.3	11	Oil City	0.370	0.79	3.7	4.7	0.377	0.79	7.0	5.1
							12	Anticline Rdge, Pad	0.251	0.49	5.2	6.4	0.420	0.72	6.7	6.0
							12	Anticline Rdge, FF	0.273	0.44	4.4	6.2	0.378	0.71	6.8	6.1
							15	Palmer Avenue	0.197	0.17	3.4	6.8	0.116	0.10	3.3	5.6
1984	IV	24	21:15	USA	S	6.2	12	Gilroy #6	0.293	0.87	10.3	7.9	0.227	0.39	7.6	7.3
1984	IV	29	05:02	ITA	N	5.4	20	Pietralungo	0.177	0.13	2.4	5.6	0.189	0.14	2.3	6.5
1984	V	7	17:49	ITA	N	5.8	59	Manopello	0.132	0.21	5.5	9.9	0.126	0.22	7.5	9.3
1984	V	11	10:41	ITA	N	5.3	2	V. Barrea	0.147	0.13	2.3	5.2	0.216	0.16	2.3	5.1
1984	X	25	09:49	GRE	-	4.7	2	Pelekanada	0.151	0.21	4.3	5.2	0.180	0.22	4.0	7.6
1985	IX	19	13:17	MEX	T	8.1	7	Caleta de Campos	0.144	0.46	27.5	26.7	0.140	0.65	30.7	17.2
							12	La Villita	0.122	0.27	36.1	8.4	0.126	0.41	37.1	15.5
							16	La Union	0.150	0.88	31.8	23.3	0.166	1.00	31.9	21.1
							45	Papanoa	0.110	0.24	9.7	13.5	0.153	0.27	13.0	14.1
1985	IX	21	01:37	MEX	T	7.5	15	Papanoa	0.207	0.36	9.3	8.6	0.242	0.49	10.1	9.2
1985	XII	23	05:15	CAN	T	6.8	9	Site No. 1	1.019	4.5	13.1	10.6	1.000	3.93	13.1	10.2
							16	Site No. 3	0.131	0.29	14.6	13.7	0.141	0.29	11.6	13.0
1986	X	10	17:49	SAL	S	5.4	6	Hotel Sheraton	0.218	0.36	5.7	8.5	0.319	0.58	5.2	7.3
1987	X	1	14:42	USA	N	6.0	19	Wilson	0.183	0.26	6.4	6.8	0.132	0.14	6.8	9.2
1989	X	18	00:04	USA	T	7.2	5	Lex. Dam. L.A	0.408	1.75	7.1	6.3	0.442	1.85	6.7	6.1
							15	Gilroy #1	0.455	1.68	9.8	6.8	0.446	1.08	13.5	9.6
							24	Gilroy #6	0.173	0.45	11.4	12.1	0.129	0.23	8.1	8.5
							35	SLAC Lab	0.282	0.95	13.6	8.5	0.200	0.58	13.4	8.8