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# STRONG-MOTION PARAMETERS: DEFINITION, USEFULNESS AND PREDICTABILITY

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## SUMMARY

Estimating strong-motion characteristics for seismic risk assessment and earthquake-resistant design requires the clear definition of parameters that reflect the destructive potential of the motion. There is currently considerable ambiguity in the definition of many parameters, in particular duration, and unqualified statements are frequently repeated regarding the usefulness of certain parameters. Current approaches to predicting the values of these parameters do not facilitate the rational estimates of the most severe earthquake motions.

## INTRODUCTION

The principal objective of engineering seismology is to provide quantitative estimates of expected levels of seismic ground-motion as the basic input to earthquake-resistant design, the evaluation of collateral seismic hazards, such as liquefaction and landslides, and seismic risk assessment. This invariably entails characterising the complex nature of strong-motion accelerograms through the use of simple parameters and the development of predictive relationships for these parameters. Since the first strong-motion accelerograms were obtained in the Long Beach earthquake of 1933, a large number of parameters have been defined to characterise salient features of the ground motion. In recent years, increasing numbers of parameters have been proposed for this purpose, many of them of increasing complexity. However, careful study of the technical literature in this field reveals that there is often considerable ambiguity or disagreement regarding the definition of even the simplest strong-motion parameters. This paper addresses this issue, discussing the definition of peak acceleration parameters and duration and the consequences of the variations, often not specified that exist amongst the definitions employed.

The usefulness of strong-motion parameters is dependent primarily upon their intended use. The parameters that can be employed in earthquake-resistant design are few and are directly related to the methods of structural analysis used in current practice. For the purposes of seismic risk assessment, through empirical loss functions relating structural damage levels to a given measure of ground-motion intensity, in theory any parameter can be employed. The usefulness of the parameter in this case will depend purely on the degree to which it is a measure of the destructive potential of the motion. It is shown that very few parameters, if any, can effectively characterise the nature of strong motion in isolation and many, by themselves, convey nothing about the destructive potential of the shaking. It is also shown that although there is often poor correlation between simple strong-motion parameters and damage levels, it is often possible to identify lower bound values for damage to occur.

Once a strong-motion parameter has been selected to characterise the ground motion, it is necessary to develop relationships between values of this parameter and features of the earthquake source, the travel path to the site and nature of the site. The nature of such predictive relationships for duration depends very heavily on the definition of duration employed. Even for a new and robust definition of duration, it is found that reliable prediction is difficult because of the dependence on features of the seismic source that cannot be predicted for future earthquakes. The way in which strong-motion parameters related to amplitude are predicted is also examined and important questions are raised regarding current approaches, particularly with respect to measures of mean values and associated scatter. The possibility of employing estimates of upper bounds on the values of some parameters is discussed.

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## DEFINITIONS OF STRONG-MOTION PARAMETERS

The most widely used parameter in strong-motion studies is the peak ground acceleration (PGA). Since accelerograms are triaxial records of the ground motion, the definition of PGA depends on how the two horizontal components are handled. Campbell (1985) lists various approaches to handling the horizontal components of accelerograms in defining PGA, the most common being the larger of the two values, the randomly oriented component (determined using both components as independent data points) and the mean of the two peaks. The second two approaches should generally yield almost identical mean values from the predictive relationships but it should be noted that the use of the mean artificially lowers the standard deviation of the regression. Boore *et al*. (1993) derive attenuation relationships, using the same data set, for both the larger and randomly oriented components, the former predicting values as much as 20% higher than the latter. The same options also exist for any other amplitude-based parameter of the horizontal motion, including response spectral ordinates for which all of the above options have been used as well as performing regressions on the spectral ordinates determined from the vectorially resolved maximum component (Kawashima *et al*., 1984).

Since the total duration of an accelerogram depends on either the diligence of the digitiser, for analogue records, or the pre- and post-event intervals, for digital records, it is not possible to define the duration of strong shaking as simply the time between the start and finish of an accelerogram. Many definitions of strong-motion duration have been presented in the literature, all of which attempt to isolate a certain portion of the accelerogram during which the strongest motion occurs. It has been found that all of these definitions can be classified into one of four generic categories (Bommer & Martínez-Pereira, 1996). The first category is *bracketed duration*, being simply the interval between the first and last excursion of a particular threshold amplitude. The second category is *uniform duration*, which is the sum of all of the time intervals during which the amplitude of the record is above the threshold. The third category is *significant duration*, which is determined from the Husid plot (Husid, 1969), usually based on the interval during which a certain portion of the total Arias intensity is accumulated. The fourth generic category is *structural response duration*, determined by applying one of these three categories of definition to the response of a specific single-degree-of-freedom oscillator. The thresholds used to define the duration, of whichever generic category, can be either absolute values of acceleration or Arias intensity, or else relative values defined as a proportion of the maximum value. A final distinction can be made between definitions based on the entire accelerogram and those determined after passing the record through a narrow-band filter to isolate a particular frequency. Table 1 lists a total of 38 studies that have proposed definitions for strong-motion duration and classifies them according to the categories that have been described. For a given accelerogram, the durations determined according to different definitions can vary by more than a factor of two. Furthermore, for weak accelerograms the definitions based on absolute criteria can result in zero duration, whereas the definitions based on relative criteria, being related only to the geometry of the accelerogram, will always yield a value of duration (Bommer & Martínez-Pereira, 1999).

## USEFULNESS OF STRONG-MOTION PARAMETERS

The strong-motion parameter most widely used in seismic design is the acceleration response spectra, although there is an increasing tendency towards the use of displacement and energy spectra (Fajfar, 1999). This move away from force-based seismic design is driven by the recognition that structural damage during earthquakes is not controlled by accelerations and hence damage can be limited more effectively by controlling either displacements or energy dissipation. For spectrum-based design methods, the type of input is limited by the method of analysis although these new trends ensure a better reflection of the destructive capacity of the motion. In time-history analysis, it is important that the accelerograms employed have appropriate values of those parameters that are closely correlated with damage capacity.

It is widely recognised that it is very difficult to characterise the nature of strong ground-motion with a single parameter, but at the same time there are other concepts regarding damaging features of strong motion which are widely repeated and yet unfounded. For example, it is often stated that the destructive capacity of ground motion increases with its duration, although by itself the duration gives no indication at all of the damage potential. For two accelerograms with similar values of PGA, the one with longer duration is likely to be more destructive, if the frequency contents are similar. However, strong-motion recordings from earthquakes in El Salvador in 1982 ($M_s$ 7.3) and 1986 ($M_s$ 5.4) revealed that in both cases the Arias intensity of the motion in San Salvador was almost identical. However, the smaller, local event produced shaking with a duration equal to about one tenth of the duration of the shaking from the larger, more distant earthquake. The transmission of the same amount of energy in a much shorter interval of time resulted in considerably greater damage in the 1986 earthquake (Bommer *et al.*, 1997).

**Table 1 Classification of definitions of strong-motion duration**

| | Bracketed | | Uniform | | Significant | | Structural | |
|---|---|---|---|---|---|---|---|---|
| Definition of Duration | Rel | Abs | Rel | Abs | Rel | Abs | Rel | Abs |
| Rosenblueth & Bustamente (1962) | | | | | | | ❍ | |
| Housner (1965) | | ● | | | | | | |
| Ambraseys & Sarma (1967) | | ● | | | | | | |
| Lynch (1967) | | | | | | | ● | |
| Husid (1969) | | | | | ● | | | |
| Kobayashi (1971) | | ● | | | | | | |
| Page et al. (1972) | | ● | | | | | | |
| Donovan (1972) | | | | | ● | | | |
| Bolt (1973) | | ❍ | | ❍ | | | | |
| Housner (1975) | | | | | ● | | | |
| Trifunac & Brady (1975) | | | | | ● | | | |
| O’Brien et al. (1978) | ● | | | | | | | |
| Hisada & Ando (1976) | ● | | | | | | | |
| Apitkaev (1977) | ● | | | | | | | |
| Trifunac & Westermo (1977) | | | | | ❍ | | | |
| Saragoni (1977) | | | | | ● | | | |
| McGuire & Barnhard (1979) | ● | ● | | | ● | | | |
| McCann & Shah (1979) | | | | | ● | | | |
| Perez (1980) | | | | | | | | ❍ |
| Takizawa & Jennings (1980) | | | | | ● | | | |
| Vanmarcke & Lai (1980) | | | | | ● | | | |
| Zahrah & Hall (1984) | | | | | | | | ❍ |
| Zhou & Xie (1984) | | | | | ● | | | |
| Shahabi & Mostaghel (1984) | | | | | ● | | | |
| Theofanopoulos & Drakapoulos (1986) | | | | | ● | | | |
| Elghadamsi et al. (1988) | | | | | ● | | | |
| Xie & Zhang (1988) | | | | | | | | ❍ |
| Mohraz & Peng (1989) | | | | | ❍ | | | |
| Theofanopulos & Watabe (1989) | | | | | ● | | | |
| Kawashima & Aizawa (1989) | ● | ● | | | | | | |
| Ellis et al. (1990) | | | | | ● | | | |
| Sarma & Casey (1990) | | | ● | | | | | |
| Papazachos et al. (1992) | | ● | | | | | | |
| Bommer & Martínez-Pereira (1996) | | | | | ● | ● | | |
| Somerville et al. (1997) | | | | | ● | | | |
| Wembo & Kezhong (1997) | ● | | | | | | | |
| Safak (1998) | | | | | | | ❍ | |
| Bommer & Martínez-Pereira (1999) | | | | | | ● | | |

● frequency-independent duration ❍ frequency-dependent duration

It is also often stated that PGA is a very poor indicator of the damage capacity, which is true, and that there is very poor correlation between observed damage and recorded values of PGA. However, using a carefully compiled dataset of 391 strong-motion recordings and 30 isoseismal maps, pairs of values of MMI and PGA were extracted and plotted in Fig. 1 (Martínez-Pereira, 1999). Notwithstanding the shortcomings of using intensity as a measure of damage, it can be clearly seen from the plot that for the motion to be potentially damaging to engineered structures (MMI ƒ VIII) the value of PGA must be at least 0.2*g*. In this way, lower bounds for potentially damaging parameters have been established for many parameters, including 20 cm/s for peak ground velocity (PGV) and 0.8m/s for Arias intensity (AI).

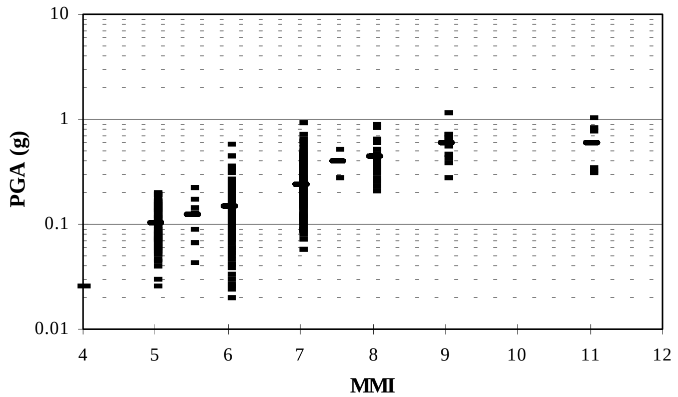


**Figure 1. Peak ground acceleration (PGA) versus Modified Mercalli intensity (MMI).**

An equally important observation that can be made from Fig. 1 is that there are clearly many accelerograms with PGA greater than 0.2*g* but which are clearly not damaging, being associated with intensity of shaking as low as VI or even V on the Modified Mercalli scale. If other thresholds, based on other characteristics of the ground motion, were also applied, for example that the PGV be greater than 20 cm/s and the damage index defined by Fajfar *et al*. (1990) be greater than 30, then many of the weak motions with PGA greater than 0.2*g* would be removed. The ability of any single parameter to measure the damage potential of the ground motion will depend to a significant degree on which features of the motion (amplitude, frequency content, duration and energy) it reflects; it is likely that any parameter which reflects any three of these properties will implicitly reflect the fourth as well. However, no damage potential parameter is of any use unless it is emprically or analytically correlated with indices or measure of damage, or at least a threshold value for damage is specified.

## PREDICTABILITY OF STRONG-MOTION PARAMETERS

Seismic hazard assessment involves estimation of the ground motions to be produced by future earthquakes. This is normally achieved through the use of attenuation relationships that predict values of a selected strong-motion parameter as a function of earthquake parameters such as magnitude and distance from the seismic source to the site. There are very fundamental difficulties encountered with current approaches to predicting strong-motion parameters and these are discussed here with reference to the prediction of duration and of amplitude-based parameters such as PGA and response spectral ordinates.

### Prediction of Strong-Motion Duration

The nature of attenuation relationships for strong-motion duration is very much dependent on the definition of duration employed. All the relationships based on durations defined by relative levels on the accelerogram or Husid plot predict values of duration that increase indefinitely with distance, whereas those based on absolute levels of acceleration predict durations that decrease with distance. The effective duration, $D_E$, defined by the authors of this paper (Bommer & Martínez-Pereira, 1999), is found to correlate well with the moment magnitude, $M_w$. Using 32 accelerograms from rock sites located at distances of less than 10 km from the earthquake source, in order to decouple the influence of distance and soil layers from the dependence on magnitude, the following relationship was found:

$$log( D_E ) = 0.69 M_w - 3.70 \quad (1)$$

The standard deviation of this regression is 0.28. Using the empirical relationship between rupture length and moment magnitude of Wells & Coppersmith (1994) and assuming a constant fault rupture velocity of 2.5 km/s, a relationship for the duration of fault rupture, $D_R$, is obtained which is identical except that the constant becomes 3.62 instead of 3.70. However, the fit in Eq.(1) is only obtained by first applying correction factors for the durations of those earthquakes caused by non-unilateral fault rupture; for earthquakes with bilateral rupture, such as Loma Prieta (1989) and Kobe (1995), the duration of shaking would be expected to be half as long and hence a factor of 2 was applied to the durations calculated for accelerograms from these earthquakes. This means that although strong-motion duration can be estimated with some confidence for a given magnitude, there will always be an uncertainty of a factor of 2 since it is not possible to know whether future earthquakes will be caused by bilateral or unilateral rupture.

## Estimates of Strong-Motion Amplitudes

Other than situations in which there are exceptional soil effects, such as in Mexico City in 1985, or topographical effects, such as ridge response at the site or Moho bounce due to path effects, earthquake motion that can cause damage to well-engineered structures is limited to within a few tens of kilometres of the source. The magnitude-distance (M-R) space in which damaging motions can be expected has been identified using a large dataset of accelerograms and defining as potentially damaging motions those passing the minimum thresholds discussed previously for PGA, PGV, AI, spectral intensity and the damage index of Fajfar *et al*. (1990), although the M-R space is almost unchanged using any 3 of these parameters (Martínez-Pereira, 1999). This limits damaging motion to earthquakes of magnitude 5 or greater and at distances which reach a maximum of 30 km at M 7.7 for rock sites and 100 km at M 7.9 for soil sites. Earthquake motions recorded at distances beyond this near-field boundary are unlikely to be of engineering significance, but generally no more than 50% of the accelerograms in the datasets used to derive attenuation relationships lie within these limits.

The values of strong-motion parameters are usually estimated from attenuation relationships that predict mean values of the parameters as a function of M, R, site conditions and sometimes other characteristics of the earthquake such as fault rupture mechanism. A typical form for such an attenuation function is:

$$log(Y) = C_1 + C_2 M + C_3 R + C_4 . log(R) \pm \sigma \qquad (2)$$

The problem arises in the way the regressions are performed using the logarithmic form of the equation as in Eq.(2), which results in records of small amplitude having the same influence on the coefficients as the few genuinely strong motions. As a result, the relationships are constrained primarily by weak records and yet the most important application is in determining the strong earthquake motion that can be generated within a few tens of kilometres of the source. The fact that these predictive equations have become known as attenuation relations, with the emphasis therefore on the decay of amplitude with distance, suggests that the focus has not been governed by engineering concerns. The recognition that strong-motion amplitudes close to the earthquake source are not reliably predicted by standard attenuation relationships has led to derivation of correction factors that take account of the effects of rupture directivity (Somerville *et al*., 1997). The application of these factors certainly improves near-field estimates of ground-motion amplitudes, but the factors rely on the *a priori* determination of source parameters which, like the non-unilateral rupture that alters duration, are difficult to estimate for future events.

Another problem associated with the use of the logarithmic form of the attenuation model is the measure of the scatter represented by the standard deviation $\sigma$, which is measured on the logarithm of amplitude. A typical value of $\sigma$ for PGA is 0.26; the mean-plus-one-standard deviation value for a small PGA of 0.05*g* is 0.09*g*, the scatter not altering the fact that the motion is too weak to be of significance in the design of new structures. However, the mean-plus-one-standard-deviation value of a near-field PGA of 0.50*g* is 0.91*g*, and the design implications of the difference are vast. In probabilistic seismic hazard assessment, the scatter is truncated at some limit, but the current options for selecting the truncation level have no physical basis. It is possible that this results in small and distant earthquakes exerting undue influence on the hazard at a site and it definitely does not provide rational estimates of near-field amplitudes. Since it is generally not possible to predict, for future earthquakes, the source characteristics that give rise to the most extreme amplitudes, the assessment of extreme seismic loading may benefit from assessment of upper bounds on amplitude parameters. It is very interesting to note that until the early 1970s many studies were published (e.g. Brune, 1970; Ambraseys, 1974) proposing, on the basis of physical models, limiting values on strong-motion parameters, several of which seem to have been confirmed by subsequent recordings (Figure 2). It is equally interesting to note that in 1971 the San Fernando earthquake produced three times as many accelerograms than had been accumulated in California over the previous 38 years: researchers could not resist the temptation of fitting curves through the clouds of data points that had become available, despite the very small amplitudes of most of the records. From then on the focus switched almost completely from the estimation of upper bounds to the estimation of mean values associated with huge scatter, which has not been significantly decreased by the expansion of strong-motion recording. As the number of accelerograms grows with expanding strong-motion networks, especially with automatic digitisation facilities and digital accelerographs, although strong records are being obtained, the proportion of weak motions in the databank is actually growing. The mean values of PGA predicted for a distance of 1 km from an M 7 earthquake by Californian attenuation relationships published over the last 30 years have gradually decreased, whereas the scatter has remained almost constant (Martínez-Pereira, 1999).

The development of performance-based design, which aims to provide greater control over structural and non-structural damage, presents new challenges for engineering seismology that may require new approaches. The parameters that control damage must be identified and unambiguously defined. When estimating ground motions for the most severe loading cases for which standard occupancy structures must be designed against collapse, upper bounds may provide a more rational approach than extrapolation across large scatter. Whichever approach is adopted, when the focus is on the most severe loading, there is strong argument for discarding a large proportion of the strong-motion dataset, which is too weak to be relevant.

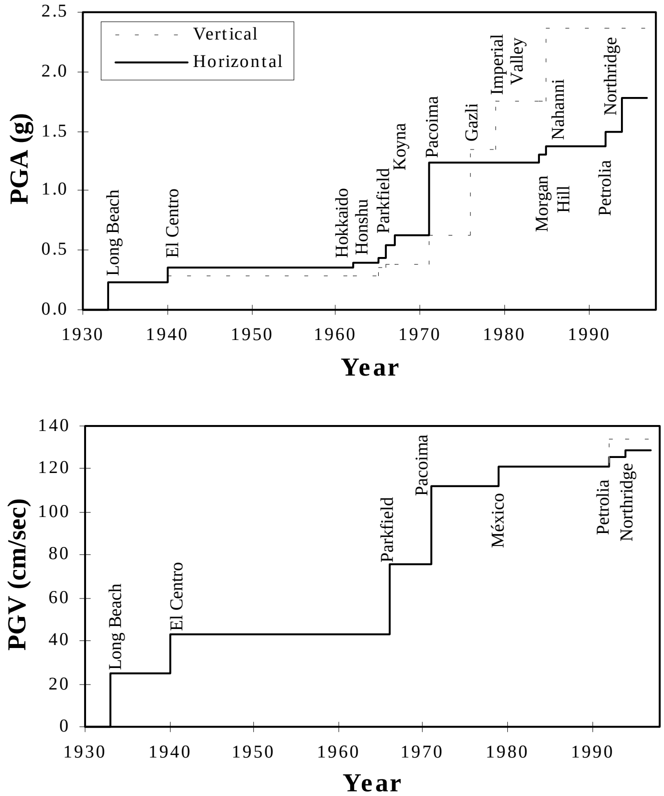


**Figure 2. Maximum recorded values of PGA and PGV (Martínez-Pereira, 1999).**

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