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THE NEED FOR UPPER BOUNDS ON SEISMIC GROUND MOTION

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SUMMARY

The usual representation of ground-motion variability using the unbounded lognormal distribution causes the hazard at very long return periods to be driven by uncertainty rather than physical parameters, which has led to extremely high ground-motion amplitudes in some important recent seismic hazard assessments. Therefore a truncation of the ground-motion probability distribution is required. To be meaningful, the definition of the truncation level has to be based on considerations related to the physical processes responsible for the bounded character of ground motion. Additional constraints on the form of the upper bound have to be included to allow a practical implementation.

INTRODUCTION

Despite a few early studies that explored the issue of upper bounds on earthquake ground motions, sometimes in a speculative manner, this topic has suffered neglect ever since the amount of recorded data was sufficient for regression analysis and the almost universal adoption of the unbounded lognormal probability distribution to represent ground motion in a way that captures its variability. The change of focus from upper bounds to general predictive equations coincided with the introduction and adoption of probabilistic seismic hazard assessment, which was able to make effective use of such equations and the assumed lognormal scatter associated with their predictions. At the return periods generally considered for engineering purposes, generally (and uncritically) set at 475 years and occasionally as high as 10,000 years, the untruncated lognormal distribution does not create any problems and hence it has not been a focus of significant attention.

However, recent studies to assess very long-term seismic hazard, such as the Yucca Mountain project in the United States (Stepp *et al.* [1]) and the PEGASOS project in Switzerland (Abrahamson *et al.* [2]), have brought the issue of upper bounds on earthquake ground motions into the arena of problems requiring attention from the engineering seismological community (Bommer *et al.* [3]). Few engineering projects are considered sufficiently critical to warrant the use of annual frequencies of exceedance so low that ground-motion estimates may become unphysical if limiting factors are not considered, but for nuclear waste repositories, for example, the issue is of great importance. The definition of upper bounds on earthquake ground-motions also presents an exciting challenge for researchers in the area of seismic

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hazard assessment, as it is directly related to the issues of ground-motion prediction and the representation of ground-motion variability.

HISTORICAL BACKGROUND

In the period between the recording of the first strong-motion accelerograms in the Long Beach earthquake of March 1933 and the end of the 1960s, a number of studies were published proposing possible upper limits on earthquake ground-motion amplitudes. Some studies were purely empirical and influenced to a large extent by the El Centro recording of the 1940 Imperial Valley earthquake: Housner [4] proposed that peak ground acceleration (PGA) would not exceed 0.5*g*; Newmark [5] proposed a limit in the range 0.5-0.6*g* on PGA and between 76 and 91 $cm.s^{-1}$ on peak ground velocity (PGV); and Newmark & Hall [6] proposed a limit of 0.75*g* on PGA and agreed with 91 $cm.s^{-1}$ as the limit on PGV. Newmark & Rosenblueth [7] refer to the estimate made by Housner [4] and argue that the upper limit must be higher, at least 1.0*g* and possibly 1.5*g*. Their argument for this latter value is based on the fact that surface accelerations in the vertical direction, exceeding 1.0*g*, had been inferred from observed effects in many earthquakes, notably the 1897 Assam earthquake; the estimate of 1.5*g* for the limit on the horizontal acceleration is then inferred from the rule-of-thumb that vertical accelerations are generally of the order of two thirds of those in the horizontal direction. A recent study by Anderson [8] using more than 3,000 seismograms from the Guerrero (Mexico) network finds that there is good agreement in general between the distribution of the V/H ratio and a lognormal distribution with mean of 0.67, but that there is a deviation from the lognormal shape in the upper 15 percent of the cumulative distribution function, where there are more high ratios in the data than the lognormal distribution would predict. Therefore, the use of the two thirds ratio to infer maximum horizontal acceleration from the maximum vertical acceleration might not be appropriate.

Other studies used simple models of slip on a fault, which were essentially rock mechanics solutions, such as Ambraseys & Hendron [9] who estimated maximum values of PGV in rock in the range of 90 to 120 $cm.s^{-1}$. Ambraseys [10] later revised the estimate to include an upper limit of 150 $cm.s^{-1}$. Hanks & Johnson [11] subsequently combined a dynamic faulting model with the limiting strength of rock to estimate a maximum PGA of 0.75*g* based on average rock strength; considering regions of higher stress in areas of greater rock strength, they estimated a more likely upper bound to be 1.8*g*. McGarr [12] performed similar analyses for inhomogeneous faulting and related the maximum ground motions to the tectonic regime, leading to maximum PGA values of 0.4*g* for extensional regimes, 2.0*g* for compressional regimes and 0.7*g* for pure strike-slip.

Table 1. Proposals for limiting values of PGA at soil sites.

Study	PGA (*g*)	Soil Type
Ambraseys (1970)	0.15	Very soft marine deposits (PI=10)
	0.30	Inorganic clays of low and medium plasticity (PI=50)
	0.50	Deposits of high plasticity
Ambraseys (1974)	0.15	Normally consolidated clays
	0.35	Highly plastic clays
	0.60	Saturated sandy clays and medium dense sands
Mohammadioun & Pecker (1984)	0.50	Near-source alluvial site
Dowrick (1987)	0.36	High plasticity normally consolidated clays
	0.61	Medium dense sands and saturated sandy clays
	1.89	Overconsolidated clays

The studies described in the previous paragraph were all based on the maximum possible strength of radiation from the seismic source. Ambraseys [13] pointed out that for the horizontal components of motion, non-linearity and the limited shear strength of soil deposits control the maximum accelerations that can be transmitted to the surface, leading to estimates of maximum PGA on normally consolidated clays of 0.10-0.15*g*, 0.25-0.35*g* for highly plastic deposits, and 0.50-0.60*g* for saturated sandy clays and medium dense sands (Ambraseys [14]). Similar values have been suggested by Dowrick [15] as summarized in Table 1. This range of values was later supported both by empirical data and theoretical non-linear models of soil response (Mohammadioun & Pecker [16]). Figure 1 shows how different estimates of limiting values on PGA and PGV have to some extent mirrored the increase in the largest recorded values of ground motion, although a more optimistic interpretation might be that the proposed maximum motions have anticipated subsequently recorded values. The critical question is whether we can still expect ground motions with amplitudes significantly higher than the largest values captured by relatively sparse accelerograph networks to date?

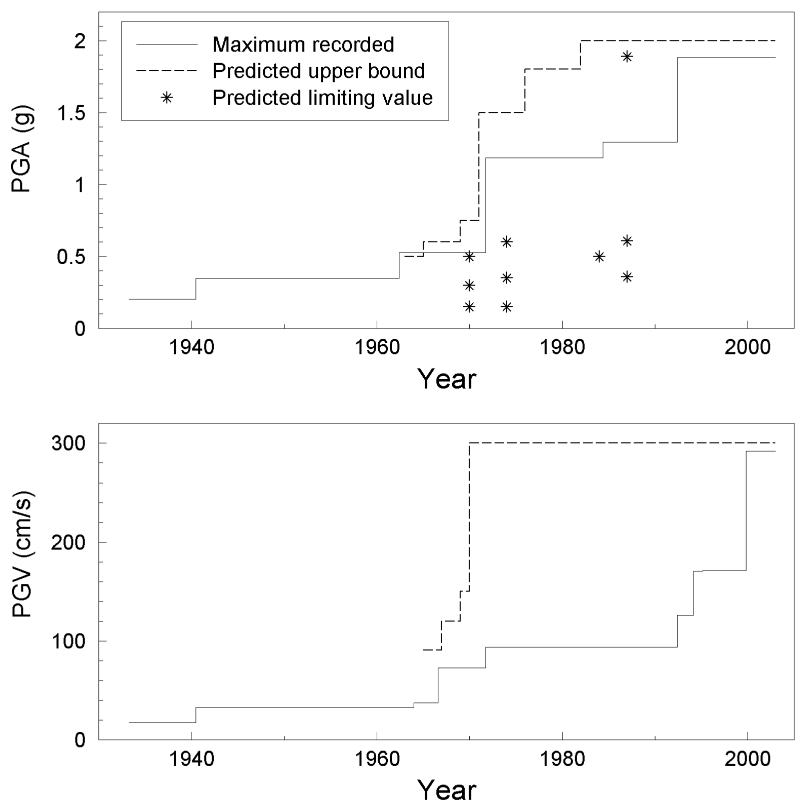

Figure 1. Relations between maximum recorded ground motion amplitudes in terms of the horizontal components of PGA (*upper*) and PGV (*lower*) and the proposed upper limits, as a function of time. In both plots, the solid line shows the maximum recorded motion, regardless of site classification of the accelerograph station. The dashed lines show the largest proposed upper bounds for ground motion amplitudes on rock (where the authors have not specified the ground conditions, it has been assumed that the estimates refer to rock sites); the maximum PGV estimate of 300 cm.s^{-1} is taken from Esteva [17], who proposed this value for the near-source saturation of peak ground velocity. In the upper graph for PGA, the stars correspond to proposed limiting values on different deposits by different studies, as summarized in Table 1 (Bommer *et al.* [3])

Following the San Fernando earthquake in February 1971, which more than doubled the databank of strong-motion accelerograms available at the time, attention shifted from consideration of upper bounds to the derivation of empirical curves through regression analysis, although there have been a few excellent studies of extreme ground motions (e.g. Oglesby & Archuleta [18]). As the database of strong-motion records has continued to grow at ever increasing rates, with expanding accelerograph networks throughout the seismically active areas of the world, the number of ground-motion prediction equations has grown in proportion (e.g. Douglas [19]). Common to nearly all of these empirical equations, often referred to inappropriately as attenuation relations, is the assumption of a lognormal distribution of the residuals, resulting in the modeling of the aleatory variability in the ground-motion predictions as a zero-mean Gaussian distribution characterized solely by its standard deviation, i.e. ground motions are formally considered to be unbounded.

At the same time that empirical equations started to be derived in large numbers during the 1970s, probabilistic seismic hazard analysis (PSHA) was becoming widely adopted in engineering practice, following the presentation of the fundamental concepts by Cornell [20]. Although not included in the original formulation by Cornell [20], the contribution of the scatter in the ground-motion prediction equations was incorporated into the calculations of annual frequencies of exceedance in the first widely available computer program for performing PSHA (McGuire [21]). The integration across the lognormal scatter in the ground-motion prediction equations has now become a standard and fundamental element of PSHA (e.g. Bender [22]). Recent engineering projects have shown the limitations of the lognormal formalism by extending PSHA to probability levels previously not explored, and thus given rise to the need to return to the issue of upper bounds on earthquake ground-motions.

WHY UPPER BOUNDS NEED TO BE DEFINED

Upper bounds on earthquake ground-motions have recently been identified as the "*missing piece*" from seismic hazard assessment, for both deterministic and probabilistic approaches (Bommer [23]). Deterministic seismic hazard assessment (DSHA) is often interpreted to define the worst-case ground motion. DSHA should therefore be based on the least favorable combination of earthquake source characteristics and location, and the strongest ground-motion that could be generated by this scenario. In practice, DSHA generally uses the logarithmic mean or mean-plus-one-standard-deviation level of ground motion from predictive equations (e.g. Krinitzsky [24]), which will generally be significantly below the worst-case scenario (Bommer [25]). If DSHA is to be used to define the maximum earthquake loading to which a structure may be subjected, then an estimate of the upper limit on the ground motion that a particular scenario could generate is needed.

Brune [26] observed that PSHA using ground-motion prediction equations with untruncated lognormal scatter may overestimate ground motions with very long return periods. This inference was based on observations of the stability of precariously balanced rocks in the Mojave Desert. The need for defining upper limits on ground motions in PSHA only becomes clearly apparent when ground motions are calculated for very low annual frequencies of exceedance. For very long return periods, the hazard estimates are driven by the tails of the untruncated Gaussian distribution of the logarithmic residuals (Anderson & Brune [27]; Abrahamson [28]). The effect of truncating the distribution at different levels above the mean is illustrated in Figure 2.

Figure 2 indicates that for the situation analyzed therein, at the 10^{-4} level – which has been widely used as the basis for seismic safety analyses in nuclear installations in the past – the difference in the resulting hazard between truncating at 3 sigmas or 6 sigmas is almost negligible. Figure 2 also clearly shows that at annual frequencies of exceedance of the order of 10^{-7} or 10^{-8}, the issue of whether the truncation level is at

3, 4, 5 or 6 sigma becomes a controlling factor on the computed hazard. The hazard curves shown in the figure are for one particular configuration and the sensitivity to the truncation level may not always be so high, particularly for sites closer to seismic source zones. Moreover, the two sets of curves indicate that the sensitivity to the truncation level is also related to the underlying seismicity rates.

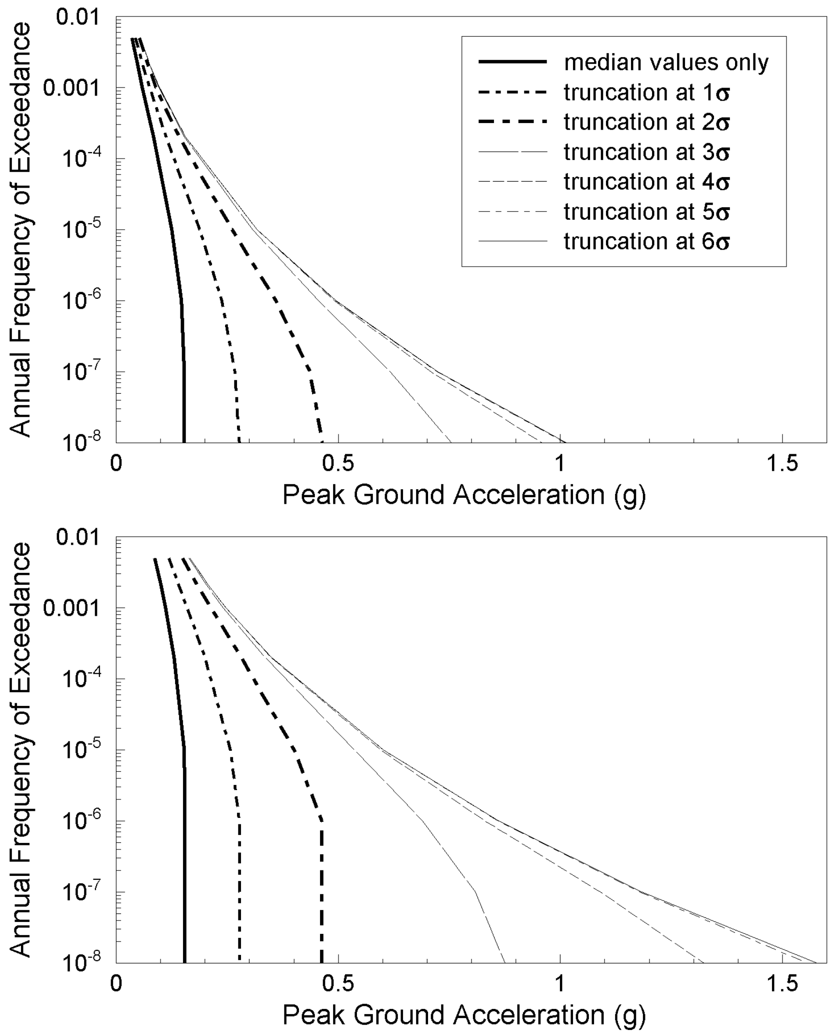

Figure 2. Seismic hazard curves derived using the ground-motion prediction equation of Ambraseys *et al*. [29] truncated at different levels of scatter. The curves are for a site at 25 km from the boundary of a hypothetical seismic source zone with a maximum magnitude of 7.5 and the *b*-value in the recurrence relationship is of 0.7 (Restrepo-Vélez & Bommer [30]). The upper graph is for an A-value of 2, the lower graph for an A-value of 3.5 (Bommer *et al.* [3])

For most engineering projects, such long return periods are of no relevance, but for the rare situations where the risk analysis must consider such extreme cases, the definition of upper bounds becomes a necessity. The PSHA carried out for the nuclear waste repository at Yucca Mountain in the Nevada desert (Stepp *et al.* [1]) considered ground motions for annual frequencies of exceedance as low as 10^{-8}, and as a result of not using truncations, extremely – and probably unphysically – high levels of ground motion were computed. For example, for a hypothetical surface site near Yucca Mountain, the PSHA showed the mean PGV at the10^{-7} and 10^{-8} values as being of the order of 6.5m.s^{-1} and about 13 m.s^{-1} respectively (Reiter [31]). Additional modifications, particularly those related to scaling real earthquake records, increased some of the ground motions even further. For example, some of the scaled ground motions at the 10^{-7} reached PGA values as high as 20*g* and PGV values of almost 18 m.s^{-1} (Corradini [32]).

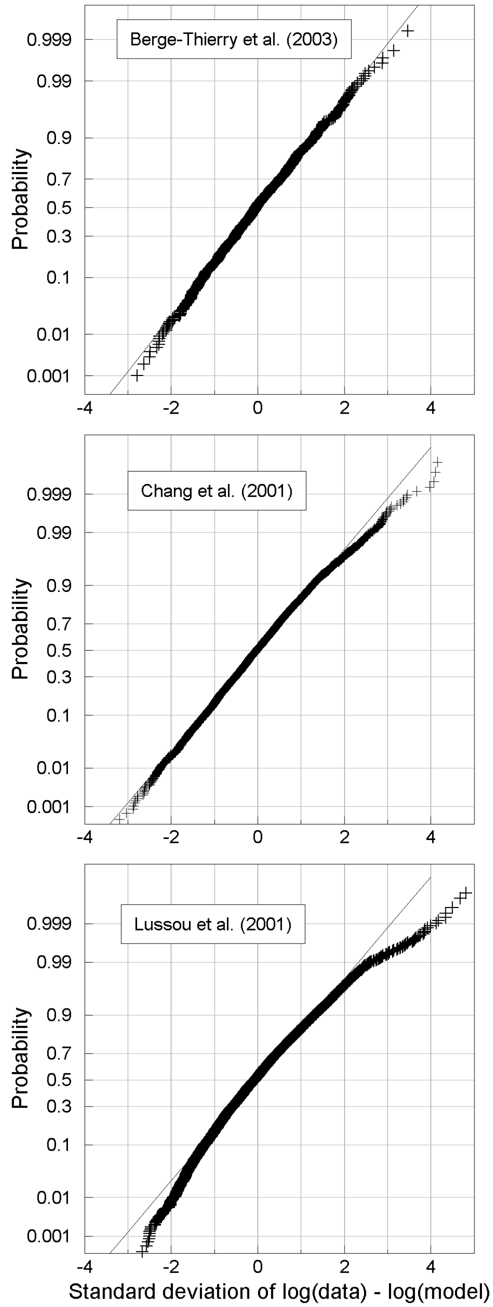

Figure 3. Normal probability plots prepared from the strong-motion data sets used to derive the PGA prediction equations of Berge-Thierry *et al*. [33], Chang *et al*. [34] and Lussou *et al*. [35]. The plots compare the distribution of the residuals with the normal distribution, and are generally used to check the lognormal assumption. These plots illustrate the fact that it is common to have data points at least 3 standard deviations above the logarithmic mean (Bommer *et al*. [3])

The Yucca Mountain PSHA has been one of the first comprehensive applications of the SSHAC Level 4 procedures (Budnitz *et al.* [36]) for expert elicitation in seismic hazard assessment. A more recent application has been the PEGASOS project to perform a comprehensive seismic hazard assessment for nuclear power plants in Switzerland (Abrahamson *et al*. [2])., which has considered annual frequencies of exceedance as low as 10^{-7}. In large part due to the outcome of the Yucca Mountain PSHA, the PEGASOS project has required experts in both the ground motion and site response sub-projects – the latter being a feature not included in the Yucca Mountain study – to specify bounding values on the ground motions.

Due to the sensitivity of the computed hazard to the truncation level, the critical point in the definition of this level is that it truly represents the boundary of physically acceptable ground motions and only excludes unphysical values. Romeo & Prestininzi [37] proposed an upper bound at two standard deviations above the logarithmic mean of the prediction equation for PGA on the basis that "*stronger motions are considered to be unlikely.*" Since two standard deviations above the mean corresponds to the 97.7-percentile, it is not disputed that higher levels are indeed unlikely, but this does not mean that they are impossible. As Agathon pointed out, "*It is a part of probability that many improbable things will happen*"; the obvious corollary to this statement, in the context of upper bounds, is that impossible things will not happen. For an equation with homoscedastic scatter (i.e. constant sigma for all magnitude and distance combinations), the upper bound will generally lie at least 3 standard deviations above the mean (Figure 3). To distinguish between improbable and impossible levels of ground motion can only be achieved if the physical processes controlling ground motions are identified, and the interactions between these processes assessed.

FACTORS DRIVING AND LIMITING EXTREME GROUND MOTIONS

Estimating the upper bound on a given ground-motion parameter at a particular site is equivalent to establishing a distinction between values of this ground-motion parameter that could actually occur at this site, and values which are only a result of simplifying assumptions during the estimation process, but do not reflect physical reality. This is a highly complex task in view of the considerable uncertainties associated with ground-motion prediction in general, and also with the applicability of existing predictive methods to the case of extreme ground motions. A necessary first step towards the estimation of upper bounds is therefore to review the physical factors that control the extreme values of motion. The maximum ground motions that can be experienced at the ground surface are controlled by three factors: the most intense seismic radiation that can emanate from the source of the earthquake; the interaction of radiation from different parts of the source and from different travel paths; and the limits on the strongest motion that can be transmitted to the surface by shallow geological materials.

The maximum amplitude of seismic radiation from the earthquake source, for a given seismic moment, is controlled by the total energy release and the rate of energy release, which are dependent on factors describing the mechanics of the rupture process, such as the magnitude of the slip, its velocity (often approximated as a function of the source rise time and the final slip), and the velocity of rupture propagation. Although the average values of these quantities generally provide a good first-order approximation, it should be kept in mind that they possess a high degree of spatial variability, resulting from heterogeneities in material properties and stress conditions across the fault plane. This needs to be taken into account since in some instances it is the rate of change of these quantities rather than their absolute value that will influence the level of ground motion. In particular, high-frequency ground motion results from abrupt changes in rupture velocity (Madariaga [38]) whereas lower frequency motions are influenced more by the actual value of the rupture velocity. While it is fully acknowledged that slip, rise time, rupture velocity and their respective rates of change are highly interdependent variables, they are presented separately in the following discussion for the sake of clarity.

For larger events, the energy release is often concentrated in small zones of the fault plane, called asperities (Aki [39]). Asperities are characterized by having much larger slip than the average over the entire rupture plane; the asperity slip contrast, defined as the ratio of average slip on the asperity to the average overall slip (Somerville *et al*. [40]), provides a first-order estimate of the relative strength of the asperity. The amplitude of the ground motions generated by an asperity can be expected to increase with asperity size (relative to the rupture area) and asperity contrast. The constraints of geometry and energy conservation however imply that both these quantities are bounded and moreover that their maximum possible values are inversely correlated. This inverse correlation can be observed in practice: in the database of Somerville *et al*. [40], the largest asperity slip contrast (3.42) corresponds to the 1984 Morgan Hill earthquake, which has one of the lowest ratios of asperity area to total rupture (0.14 compared to the average of 0.22). Conversely, the largest relative size of asperities (0.4) is identified for the 1983 Borah Peak earthquake, which has an asperity slip contrast of 1.62, well below the sample average of 2.01.

As discussed previously, details of the slip distribution (e.g. the slip contrast between the edge of the asperity and the surrounding region) might also be important, in particular for the generation of high-frequency motions. However, the importance of these details decreases with increasing distance from the source. For sites located far enough away from the source, the effect of the source on ground motions can be satisfactorily estimated using the average value of slip velocity. While the slip distribution reflects spatial variations in the density of energy release, the distribution of the slip velocity gives an indication of the rate at which this energy is released.

The velocity of fault rupture will also play a role in controlling the most extreme ground motions that can be generated, since rupture velocity affects the corner frequency of the radiated body waves. In a study of the 1906 San Francisco earthquake, Boore [41] finds that a change of rupture velocity from 2 to 3 km/s led to a four-fold increase in computed ground motions at periods of about 5 seconds. Boore & Joyner [42] investigate how the introduction of incoherence into the smooth propagation model of Boore [41] affects the outcome and conclude that the sensitivity of near-field ground motions to rupture velocity and azimuth is preserved as long as the mean rupture velocity is the same. It should however be kept in mind that the figure quoted above is the result of a modeling exercise, rather than an observed quantity.

If the spatial variability of rupture velocity across the fault plane is considered, the definition of the maximum permissible values of this quantity becomes even more of an issue. Das [43] discusses the development of proposals regarding maximum permissible rupture speeds, addressing in particular the issue of whether rupture velocity can exceed shear-wave velocity. The answer to this problem is to a large extent dependent on the assumptions of the model that is used. Day [44] uses a finite difference method to study crack propagation in a 3D continuous medium. He finds that in cases where super-shear velocity is predicted by a uniform pre-stress model, the introduction of stress heterogeneities is sufficient to reduce the average rupture velocity to less than the shear-wave velocity, while local super-shear rupture velocities can still occur in regions of high pre-stress. Day [44] concludes that rupture models including extensive segments of super-shear propagation should not be considered unphysical, even when the average rupture velocity can be reliably determined to be sub-shear.

Although the issue of super-shear rupture velocity has been considered for some time (e.g. Murray [45]; Archuleta [46]), it is still a matter of controversy. One reason for this is that the complexity of the inversion problem makes it difficult to know to what extent the computed variables trade off with each other. For example, in the kinematic model of the 1979 Imperial Valley event presented by Archuleta [46], the zones corresponding to super-shear rupture velocities at the bottom of the fault plane are associated with high slip and short rise time. Another consequence of the complexity of the inversion problem is that it is highly sensitive to the quality of the data used to calibrate it, as illustrated by the recent Kocaeli event.

Bouchon *et al.* [47] find that the central segment of the fault broke at the super-shear speed of about 4.8 km/s. In the same issue, Sekiguchi & Iwata [48] examine both the hypothesis of super-shear rupture and the alternative explanation of a P-wave triggered asperity to account for the anomalously short S-P time at the Sakarya (SKR) station, and conclude that the latter is the preferable interpretation. Therefore, although new evidence in favor of extended super-shear rupture (e.g. Bouchon & Vallée [49]) should not be ignored, the issue of the maximum proportion of the fault plane that can undergo super-shear rupture still requires further investigation.

In the discussion above, the focus has been on the mechanical aspects of seismic rupture. As a consequence, the spatio-temporal characteristics of energy release are considered from the point of view of an observer located on the source. The advantage of this viewpoint is that it gives a detailed insight into the source processes that will control the ground motion leaving the source. However, little information is gained on how these source effects interact with propagation effects to ultimately produce extreme ground motions.

An alternative approach is to look at the problem from the receiver point of view, i.e. examine the temporal distribution of seismic radiation arrivals at a given geographical location. From this perspective, the amplitude of ground motion at the location of interest at a given moment in time is simply the algebraic sum of the amplitudes of all the waves arriving at this location at that instant. In most cases, the maximal amplitudes of different wave trains will arrive distributed in time; it can also happen, however, that two or more wave trains reach their peak value simultaneously at a given location. This phenomenon is known as constructive interference. Constructive interference can be an isolated occurrence in time, which will lead to a single spike in the amplitude of the motion, without changing significantly the amount of energy that arrives at the location of interest. However, in the particular case of the arrival of two or more coherent waves, i.e. waves that travel with a constant phase difference, all the peaks and troughs will arrive simultaneously, leading to a significant increase in energy. This phenomenon only affects locations satisfying a number of geometric constraints defined by the location of the elementary sources emitting the waves. Elementary sources can be of two types: separate areas of the rupture plane (possibly triggered at different moments in time with different rupture velocities) and secondary sources such as reflection or refraction interfaces. As a result, there are numerous scenarios that can lead to increased ground motions due to constructive interference along the propagation path. Close to the source, constructive interference is mainly the result of simultaneous arrival of contributions from different parts of the rupture plane, as a consequence of the spatial variability of rupture velocity across the fault plane discussed previously. Examples include forward directivity (e.g. Somerville *et al.* [50]), and focusing of energy towards a station located along the axis of symmetry of the rupture (e.g. Oglesby & Archuleta [17]). Also, for an extended source, late arrivals from the part of the fault where rupture initiates can reach the site at the same time as early arrivals from a part of the fault that ruptures later (e.g. Anderson [51]). Farther along the propagation path, constructive interference is essentially the result of particular geometrical conditions leading to reflection or refraction of the waves in a preferential direction and thus to focusing of energy. Examples include increased amplitudes at the tip of the wedge above the hanging wall (e.g. Oglesby *et al.* [52]) and topographic effects. The latter can be due to features of the surface topography, such as hills (e.g. Bouchon & Barker [53]) or canyons (e.g. Boore [54]). Subsurface topography can also be the cause of constructive interference; the most prominent example is the interference of surface waves generated at the edge of deep sedimentary basins with direct arrivals, as observed for instance during the 1995 Kobe event. Also, the presence of local heterogeneities in the substratum can result in focusing of energy towards a particular area, as was the case for Santa Monica during the Northridge event (Gao *et al.* [55]).
As seismic waves propagate to the Earth's surface, other factors act to limit the maximum amplitude of the motion. These factors are associated with the failure of surface materials, which are usually weaker than the underlying rock, under the loading conditions generated by the passage of seismic radiation. The

principle is similar to that of a fuse: once failure is reached at a given depth within the soil profile, the incident motion is filtered and no motion larger than the motion reached at the failure stage can be transmitted to the upper strata.

Following a postulate by Schnabel *et al.* [56], it is generally assumed that the strong part of horizontal motion in soil deposits is mainly caused by the vertical propagation of SH-waves, while the strong part of vertical motion is caused by the vertical propagation of P-waves. This simplified representation requires two conditions to be met: firstly, the soil profile must be almost horizontally layered – which is a reasonable assumption in view of the mechanics of soil deposition and weathering – and secondly, the propagation must be vertical. This latter assumption is usually justified by the fact that the stiffness of surface materials decreases towards the surface, causing the wave path to undergo successive refractions and thus becoming nearly vertical.

Under these assumptions, any soil element within the profile will be submitted in the horizontal direction to cyclic simple shear strains and in the vertical direction to constrained one dimensional compression-extension strains. For these simplified stress paths constitutive soil modeling (e.g. Prévost [57]) predicts that a failure condition can be reached only for the simple shear condition. Therefore, it can be anticipated that the horizontal ground motion is limited by the soil strength, whereas the vertical one is fully transmitted to the ground surface. Such anisotropic behavior has been observed in the field: Aguirre & Irikura [58] examine accelerograms recorded during the 1995 Hyogo-ken Nanbu earthquake on the vertical array at Port Island, Kobe, where liquefaction occurred. They find that the recorded horizontal peak acceleration was only about 25% of the value expected from linear theory, while vertical peak acceleration was close to predictions from linear theory.

However, as Beresnev *et al.* [59] point out, the discussion above only holds if propagation is strictly vertical. This stems from the fact that even a small non-zero incidence angle would significantly increase the contribution from SV-waves to vertical ground motion, because they are associated with larger amplitudes than P-waves. A spectral study of the vertical motions recorded during five significant recent events recorded in California yields the result that for frequencies up to 10 Hz, the vertical ground motion is dominated by SV-waves rather than P-waves. If this threshold is to be considered robust, the validity of the conclusions reached in the previous paragraph is limited to PGA; for lower frequencies, all components of motion could be expected to be limited by soil strength.

TOWARDS A COMPREHENSIVE DEFINITION OF UPPER BOUNDS

The previous discussion has established the need for upper bounds in seismic hazard assessment and the indispensable character of a physically-based definition. A preliminary review of physical factors influencing the values of ground motion has highlighted both the great number and variety of factors to take into account and the complexity of the interactions between them. This complexity cannot be neglected if a meaningful estimate of the upper bound is to be obtained. Therefore the next step towards estimating upper bounds should consist in a careful review of the tools available for ground motion prediction. In particular, strong-motion records with unusually large levels of ground motion (as defined by thresholds on one or several parameters) need to be reexamined in order to gain more insight into the relation between the level of ground motion and the physical mechanisms controlling it (e.g. Anderson *et al.* [60]). However, despite the considerable amount of strong-motion records available nowadays, empirical data on its own is still insufficient to constrain the values of extreme ground motions, mainly because of the incompleteness and the strongly heterogeneous character of the dataset represented by the global strong-motion holdings. The information gained from extreme empirical motions thus needs to be supplemented by theoretical models simulating the generation and propagation of seismic waves from the source to the site. The use of these theoretical models allows a physically meaningful extrapolation of empirically derived correlations between explanatory factors and ground-motion level to situations for which little or no data is available, provided that both the applicability and the compatibility of these tools is ensured. Applicability is an issue because existing ground-motion prediction models have been developed to estimate average motions and might be inappropriate for extreme ground motions. Compatibility between methods and assumptions should be examined to avoid double-counting of physical factors or misuse of the tools.

The requirement of a physical basis, however hard to meet, is absolutely essential to the definition of upper bound ground motions, and should be the main focus of research on that subject. There are, however, a number of additional constraints on the formulation of this definition to ensure its usefulness in practice, and giving these issues a thought at an early stage of the development of a general framework for upper bounds will certainly help to ensure its inner consistency. In particular, any definition has to be compatible with the needs of seismic hazard assessment for critical facilities, i.e. it has to give an estimate that makes the best use possible of available information and knowledge relevant to the problem under consideration. The issue is not solved by simply defining the maximum level of ground motion that could ever be achieved. Upper bounds need to be defined, possibly on a regional basis (and certainly separate definitions will be needed for crustal and for subduction earthquakes) as limiting surfaces defined by at least the following parameters: magnitude, style-of-faulting, depth of faulting, source-to-site distance and site conditions, which will almost definitely need to consider both the strength of the materials in the upper tens of meters at the site and the structure over a depth of several kilometers. The simple procedure illustrated in Figure 2, of truncating at a specified number of logarithmic standard deviations above the logarithmic mean of the ground-motion prediction equation, is unlikely to be an adequate solution. Amongst the reasons for this is the fact that in a logic-tree formulation truncating different attenuation relations in this way will not define a unique surface of bounding values.

Another important point to be borne in mind is that some simplifying assumptions and artificial boundaries between self-contained models that have been shown to work well in predicting average ground motions will have to be dropped in the case of extreme ground motions. For instance, to obtain the strongest possible ground motions at a particular distance from the fault rupture using seismological source models, the high spatial variability of ground motions needs to be considered. While it is useful from an analytical point of view to separate between the effects that contribute to creating and limiting extreme ground motions, the final model for upper bounds will need to consider the interaction between the two, since the nature of site response is dependent upon the base excitation.

There is also a potential pitfall in determining upper bounds if analyses are performed for individual strong-motion parameters and then hazard analysis is carried out allowing each parameter to reach its *maximum maximus* value. The total energy liberated by a fault rupture will always be limited since the seismic energy released per unit of the source volume is approximately constant; extreme ground motions are therefore likely to be created not so much by generation of very high amounts of energy but rather by the focusing of the energy into particular period ranges. Source effects such as rupture directivity will generally affect longer period motions; site effects will often cause focusing of the energy into a narrow frequency band. Therefore, a vector approach may be needed, following the proposal of Bazzurro & Cornell [61], in which PSHA is performed for two ground-motion parameters simultaneously, including a model for the covariance of the residuals of each parameter to calculate the joint probability distribution. As has been suggested by Restrepo-Vélez & Bommer [30], this concept could be extended to the definition of upper bound ground-motions since the latter correspond to the maximum residuals.

The simultaneous evolution of amplitude and duration will require particularly close attention as, although the definition of upper bounds on ground-motion amplitudes will always correspond to the largest absolute values, for source effects the most extreme ground motions, in a general sense, will probably correspond to the shortest possible duration of shaking for a given magnitude. There may be situations, particularly with regard to liquefaction hazard for example, where long duration of shaking will define the worst-case scenario, but for structural response (except for strongly degrading structures) the worst-case scenario is likely to be related to the amplitude of the ground motion even though it has shorter duration. Short duration of shaking, whereby the major part of the Arias intensity is accumulated in a short interval, can be driven by bi-lateral rupture and high rupture velocities (Bommer & Martínez-Pereira [62]) and by forward directivity effects (Somerville *et al.* [50]).

CONCLUSIONS

The experience of the Yucca Mountain and PEGASOS seismic hazard studies, both of which have considered very small annual frequencies of exceedance for safety critical structures, has raised the importance of the issue of upper bounds on earthquake ground motions (Bommer *et al*. [3]). A great deal of work will need to be done before reliable and robust solutions can be provided, requiring input from and interaction between seismological source modelers, strong-motion seismologists and experts in soil dynamics. The outcome of this work, however, will be of great use to engineering seismology in general, providing the ultimate 'reality check' for PSHA as well as defining the elusive "worst case scenarios" that proponents of DSHA claim to specify. Although the research may be driven by the needs of a very small number of very special projects, the work is likely to be of more general use, defining the limits of the hazard space, identifying factors that increase or limit hazard levels, and improving, in the process, the capability to model ground motions and site response.

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