Design earthquake estimates for dam sites: methods and considerations

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ABSTRACT:
The methodologies to be used in the seismological studies to characterize the Maximum Credible Earthquake (MCE) are not very well established. In this paper some progress and considerations about common methodologies presently used to assess the seismic input parameters are discussed.
Probabilistic seismic hazard analysis and deterministic seismic analysis using attenuation laws (ground motion prediction equations - GMPEqs) are widely used approaches. However, there are significant disadvantages in their use namely: (i) the MCE is not considered a finite source and (ii) the applicability of GMPEqs for magnitudes and distance of interest is sometimes uncertain.
Being so, the definition of the MCE could be based on finite-fault modelling (FFM), which allows reproducing effects that influence amplitudes, frequency content and duration of ground motion. In this paper, the FFM is applied to assess MCE for some Portuguese large dams and it is emphasized its feasibility to synthesize ground motion at a dam site.

Keywords: dam, maximum credible earthquake, finite-fault stochastic model

1. INTRODUCTION

Recently, a series of critical hydropower projects have been under study. Specifically, 11 new dams will be constructed in the following years, in Portugal mainland.

The seismic actions that should be considered in large dams design are well defined in ICOLD (International Commission of Large Dams) Bulletins and also in Portuguese dam safety regulations, foreseeing the use of two types of earthquakes: the Operating Basis Earthquake (OBE) and the Maximum Credible Earthquake (MCE). However, the methodologies to be used in the seismological studies to characterize those earthquakes are not so well established, mainly for the MCE.

Two approaches, probabilistic seismic hazard analysis and deterministic seismic analysis using attenuation laws are widely used in deriving the ground motion parameters for design purposes. However, for both approaches there are two relevant weaknesses affecting ground motion at the dam site namely (i) the MCE is considered a point seismic source and (ii) the ground motion prediction equations (GMPEqs) applied so far, for Portugal mainland sites, were based on international attenuations laws derived for others regions and theirs applicability and extrapolation for magnitudes and distance of interest becomes rather uncertain.

In fact, in Portugal, insufficient accelerograms have been recorded to satisfactory undertake any regional empirical study. The number of accelerograms is not only small but also refers to low-magnitude earthquakes located in only some parts of Portugal entire seismogenic area. For that reason, most prediction techniques of ground motion in Portugal have not been based on regional data to quantify the characteristics of ground motions. However, differences in the regional geology can led to variations in ground motions characteristics and the use of empirical laws of other regions is questionable and may not be appropriate for Portugal.

As prediction cannot be based on empirical analyses, well-founded physical models must be used as the basis for the predictions of strong motion in Portugal. These models should provide the means to make extrapolations to the range of magnitudes and distances of interest, and over the entire frequency range of engineering interest, with confidence.

Moreover, the effects of a large finite source, including rupture propagation, directivity and source geometry can profoundly influence the amplitudes, frequency content and duration of ground motion. The development of stochastic based ground motion synthesis associated to a seismological finite-fault modeling is a worldwide approach that can be used for representation of future large magnitude earthquakes occurring in Portugal, allowing the reproducing of specific source effects like directivity and asperities distribution, and path and crustal effects. This modeling technique is now being also used to develop regional ground motions prediction equations in many regions of the world (eg. Atkinson & Boore, 2006; Motazedian & Atkinson, 2005; Sihua & Lung, 2004).

In this paper, stochastic finite-fault methodology is applied to assess the MCE, showing that its application could lead to better approaches of seismic safety assessment of Portuguese large dams.

2 MCE ASSESSMENT: CONTEXT, PROBLEMS AND RECENT DEVELOPMENTS

2.1. Definitions

The Portuguese Standards for Dams, similarly to the recommendations of ICOLD (1989), establish that the seismological studies should lead to the definition of seismic actions, particularly the magnitude, shape and duration of seismic vibrations at the dam site, considering three types of seismic actions:

- The Maximum Credible Earthquake (MCE), which should be estimated either by deterministic or probabilistic ways, in the latter case, the MCE should be considered an earthquake with a rather long period;

- The Maximum Design Earthquake (MDE), which, for dams with a high potential risk, should be taken as the MCE, but, in other cases, may be lower;

- The Operating Basis Earthquake (OBE), less intense than the MDE, with a recurrence period set according to the potential risk involved.

The definition of MDE is linked to the concept of maximum credible earthquake (MCE), which is the largest earthquake that can be physically generated by a fault in the region and recognized under the current tectonic knowledge. Each active fault or tectonic province is thus associated with an MCE, representing therefore an upper limit of magnitude or epicentral intensity forecast. The MCE from which may result the higher consequences for the dam is called the Controlling Maximum Credible Earthquake (CMCE) (USCOLD, 1999). The CMCE is thus an earthquake that generates an upper limit of the seismic motion expected at the site of the dam, equivalent to the MCE. It does not necessarily correspond to any earthquake that has occurred in the region. It is, by definition, an idealization that represents a possible earthquake with a large recurrence period and whose evaluation is necessarily based on a deterministic approach.

For the Maximum Design Earthquake (MDE) the dam should behave so that the damage, although significant, do not cause casualties or substantial economic and environmental damage, on other terms, do not cause uncontrolled leakage of water from the reservoir.

The Operating Basis Earthquake (OBE) is the seismic movement likely to occur one or more times during the lifetime of the dam. The OBE is usually defined as the level of seismic movement on the site with a 50% probability of not being exceeded in 100 years (lifetime of the dam), which corresponds to a recurrence period of 145 years. For this action it will only be tolerable minor damage that does not affect the functionality of the dam.

2.2. Widely used approaches and obstacles

Earthquake ground motions, including peak values, response spectrum, duration and time histories are parameters of input ground motion. As mentioned, two approaches are widely used: Probabilistic seismic hazard analysis (PSHA) and deterministic seismic hazard analysis (DSHA). The two approaches may use the same data sets (both approaches have the problematic issue of identifying potential sources) and the same GMPEqs but the final products differ from each other.

The essence of PSHA is to identify all possible earthquakes that could affect a site and to provide a quantitative assessment of seismic hazard, described by the likelihood that various levels of ground motion at a site will occur or will be exceeded at a given location in a given time period. It is based on integrating the seismic source characterizations and ground motions estimates (with the use of adequate GMPEqs). The output of PSHA are estimates of seismic hazard curves and the ground motion derived are not associate with any individual, but many earthquakes, and so the ground motion does not have a clear physical meaning. Using this approach, the MCE is determined by extrapolating the hazard curve to the event with a rather long period, with the inconvenient of large extrapolation.

In DSHA, a source zone is considered separately (an earthquake scenario, defined in most cases by a magnitude and a distance) the output being a ground motion corresponding to a single event in a single source.

For engineering design it is desirable to determine the ground motion for a “design earthquake”, and that way DSHA is more appropriate to developing the ground motion time histories. It is worth noting that this scenario earthquake can be the result of the deagggregation of seismic hazard, meaning the event –magnitude and distance- that dominate the seismic hazard for a specific return period. This does not contradict the DSHA herein focused, as in this paper context DSHA is not the upper bound or the worse case scenario, but an event defined by magnitude and location whose ground motion are calculated as the median, and perhaps a median-plus-one standard deviation, values from GMPEqs.

However, for both PSHA and DSHA, the key components are the GMPEqs. A major shortcoming of all predictive ground motion models developed is that for stable continental regions such as Portugal they are based on relatively scarce observational data, obliging the use of non regional empirical laws and, consequently, a great uncertainty is associated to the applicability and extrapolation (in magnitude and distance) of those regressive relationships and, consequently, to analysis and results.

Besides ground motion amplitudes (meaning in PSHA and DSHA, equations relating magnitude and distance to peak ground accelerations peak ground velocity and/or other spectral values) duration is a very important parameter for the complete determination of structural response from an earthquake and this is available from the time histories of the ground motion. However, as this is the case of Portugal, there are no recordings available of earthquakes of the proper size or from the seismogenic source pretended. Being so, artificially generated time-histories (even though corresponding as closely as possible to the given design spectra) are obtained using empirical duration equations, which in turn contributes also to a great uncertainty. Furthermore, the widely used techniques usually generate artificial time histories that do not adequately reproduce the nonstationary nature of seismic motion.

Another obstacle of both commonly used approaches is that MCE has still been regarding as a point seismic source (ground motion is estimated based on magnitude and the minimum distance from he source-zone or fault to the site) and several phenomena observed in strong motion can only be understood and synthesized in the context of finite source models.

In conclusion, as it is clear the importance of a finite-source model that have de advantages of taking into account source geometry, heterogeneities of rupture and directivity effects, MCE should be regarded as a finite fault source. Moreover, for Portugal, it is necessary to synthesize ground motion for MCE based on physical methodologies that do not use empirical statistical prediction equations for parameters of input ground motion, a major obstacle for the use of current seismic hazard analysis.

2.3. Recent developments, in Portugal

For a realist and feasible ground motion prediction it is important to use a set of assumptions about the earthquake source spectrum, effects of path and site conditions. To make allowance for these effects, the methodology applied for ground motion characterization at the Portuguese dams combines:

(i) the finite-earthquake-source modelling technique (Beresnev & Atkinson, 1998) that includes a fault discretized into several elements (sub-faults), a nucleation point (initial point of the rupture), an heterogeneous slip distribution, a rupture velocity and the summing at the site of the dam of the contribution of each element lagged in time;

(ii) the source-point stochastic model (Boore, 1983): each element of the fault is modelled as a stochastic omega-square point source, the amplitude of the acceleration Fourier spectrum for each subfault is calculated as a product of the spectrum produced by the source at a certain distance and filtering functions representing the effects of path attenuation and site response.

The non-stationary stochastic finite fault simulation method, herein called RSSIM (Carvalho *et al.*, 2008) was applied to calculate response spectra and to synthesize accelerograms for 3 new hydropower projects in Portugal. The RSSIM has been implemented starting from the classic simulation code FINSIM (Beresnev & Atkinson, 1998) and then EXSIM (Motazedian & Atkinson, 2005) widely employed in the seismological literature for simulation of the ground motion from both moderate and high magnitude earthquakes.

RSSIM is a method that synthesizes the ground motion due to an extended source by means of an appropriate number of sub-sources, radiating as ω^2 point sources. Like FINSIM and EXSIM, the RSSIM method assumes that the fault plane is a rectangle, subdivided into an appropriate number of sub-faults. The amplitude of the acceleration Fourier spectrum for each sub fault is calculated, as said before, as a product of the spectrum produced by the source at a certain distance, $S(\omega)$, and filtering functions representing the effects of path attenuation and site response. If the site receiver can be characterized as hard rock, the amplitude of the acceleration Fourier spectrum is given by:

$$A(\omega,R) = \omega^2 \cdot C \cdot S(\omega) \cdot G(R) \cdot An(\omega,R) \cdot P(\omega) \quad (2.1)$$

where C is a scaling factor including the free surface amplification factor, the radiation pattern of shear waves and the energy partition into the two horizontal components, $S(\omega)$ is the amplitude displacement source spectrum, $G(R)$ is the geometric spreading factor, $An(\omega,R)$ is the anelastic path attenuation factor and $P(\omega)$ accounts for the upper crust attenuation. The functional form of all these factors and the respective physical meaning can be found elsewhere (eg. Boore, 2003; Carvalho *et al.*, 2008; 2009).

The ground motion at an observation point is obtained by summing the contributions over all sub faults. An element triggers when the rupture reaches its centre. The contributions from all elements are lagged and summed at the receiver, the time delay for an element being given by the time required for the rupture to reach the element, plus the time for shear wave propagation from the element to the receiver. The duration of motion comes from the source duration plus the path duration.

However, RSSIM differs from the classic FINSIM or EXSIM as it avoids, if only the response spectrum is desired, the computation of acceleration time series representing the contribution of each sub-fault (nevertheless it has that option when time series are the final goal), but synthesizes the ground motion due to the entire fault from the Power Spectral Density Function (PSDF) radiated by each sub-fault, using the random vibration theory and the extreme values statistics (ex. Vanmarcke, 1976; Boore & Joyner, 1984; Boore, 2003). This has the advantage of calculate response spectra and peak values in a more straightforward approach and in a faster computer way. Detailed procedures can be found in Carvalho *et al* (2008).

Finite-fault simulations require that the fault-plane geometry (length, width, strike, dip, number of subfaults considered and depth to the upper edge), the source parameters (seismic moment, slip distribution, stress drop, nucleation point, rupture velocity), the crustal properties of the region (geometrical spreading coefficient and anelastic attenuation) and the site-specific soil response information be previously specified.

The model parameters calibration has been obtained with a dataset that includes horizontal components of ground acceleration records (at rock sites) obtained by the Portuguese digital accelerometer network and from independent studies. Validation, by comparing synthetic seismograms against recorded ones, were done entirely in terms of 5% damped pseudo absolute response spectra for acceleration (Carvalho *et al.*, 2008; 2009).

The demonstrated agreement between model and data for low to moderate events in Portugal provides strong grounds for accepting the stochastic-process model predictions and to use it as the basis for characterization of stronger earthquakes considering a finite fault rupture model and as a tool to develop regional ground motion predictions equations. Empirical characterization of strong motion data will also need to continue as they are a key parameter for use in engineering design and seismic hazard analysis. Physical modeling, with calibrated parameters, will help to understand factors controlling largest earthquakes ground motion and to improve predictions, allowing progress and reducing uncertainties in seismic analysis. It is therefore worth mentioning that the calibrated model was used to create a data-base with magnitudes and distance range of interest, allowing then to derive ground motions predictions equations for Portugal.

3 MCE ASSESSMENT – AN APPLICATION

To account for the uncertainty in model parameters, and to estimate upper bound for the seismic input of MCE, we perform a large number of runs for the same fault plane (MCE scenario). Following Atkinson & Boore (2006), we considered the effects of aleatory uncertainty, expressing random variability in the parameter from one ground motion realization to another. Each key parameter (length, width and strike of the fault, stress drop, upper crustal attenuation and geometric-spreading coefficient) was treated as a probability distribution (truncated normal or uniform distributions, depending on the parameter which is being modeled). As in Atkinson & Boore (2006), the uncertainty in duration is not modeled as it is less significant than uncertainty in other parameters in terms of its impact on simulated ground motion amplitudes, the same for physical constants.

The mean values of input parameters to the model are considered well established previously (Carvalho *et al*, 2009). It is important to mention that it is not our intention to express uncertainty in a mathematical consistent way but model random fluctuation in the actual effective values obtained for the parameters, in order to obtain estimates of the *likely range of the upper bound on some parameters* (Boomer, 2002*)*. Details on aleatory uncertainty considerations can be found in Atkinson & Boore (2006).

Source parameters:
For a hidropower project in the North of Portugal the MCE was assigned to be a 6.2 magnitude earthquake. The region where the dam will be implemented is a low seismicity zone, being the Penacova- Régua-Verin fault (PRVF) the most prominent structure expressed, at 20km from the dam site. The overall expression of PRVF in the area of the hydropower project indicates that this fault is a NNE-SSW trending structure, the principal movement is strike-slip and that has evidence of

quaternary activity (Baptista, 1998).

Fault dimensions were calculated using empirical relations of Wells & Coppersmith (1994) for strike-slip faults, relating moment magnitude and length and width of the fault. These regressive equations were considered as an upper bound for fault dimensions, which were allowed to have a variability, multiplying length and width by a normally distributed factor truncated, so that the factor taken as 0.8 ± 0.2 could not be greater than 1 nor less than 0.4. The fault strike was inferred from the geological map (Serviços Geológicos, 1992), taken as N30ºE ± 10º and treated as a normal distribution truncated.

Slip model is a very important source of variability in ground motion simulations. However, the random slip distribution, for all range of frequencies, seems a correct assumption when slip distribution of an earthquake is not known or for predictions of strong ground motion for future earthquakes.

The most important source parameter is the stress drop, which controls the spectral magnitude at high frequencies. Following Carvalho *et al*. (2009) we adopted a median stress parameter of 101 bar and expressed its uncertainty by a normal distribution in log stress with mean 2.02 log units and a standard deviation of 0.2 units, corresponding to a factor of 1.5 variability.

Median source parameters values assumed for the stochastic simulation are summarized in Table 1, together with variability (uncertainty) adopted for some of the parameters.

Table 1. Median source parameters and uncertainty

Parameter	Median value (mean)	Distribution type	Standard deviation	Min	Max
Moment magnitude	6.2				
L (km) x W(km)	15 x 8				
Dimension factor	0.8	Truncated normal	0.2	0.4	1
Strike (NºE)	30	Truncated normal	10	20	40
Dip (º)	90				
Depth to upper edge of the fault (km)	5				
Slip model	Random				
Stress (bar)/ log stress	101 / 2.02	Log normal	0.2		
Velocity of rupture (km/s)	2.5				

Path parameters:
As regard to crustal attenuation properties, for the inelastic attenuation (An(ω,R) in Eqn. 2.1) we adopted the frequency-dependent quality factor $Q(f)=250\ f^{\,0.7}$ of Pujades *et al* (1990). Considering geometric attenuation, G(R) in Eqn. 2.1, a tri-piece-wise function described by Atkinson & Boore (1995) was used, assuming a crustal seismogenic thickness of 31 km (Jiménez–Munt *et al*., 2001). Shear wave velocity is assumed to be 3.5 km/s with density 2.8 g/cm^3.

Uncertain of attenuation with distance, both geometric and inelastic, should, of course, be taken into account. Atkinson (2004) showed that geometric spreading is significantly faster at near-source distances (1.5 times the crustal seismogenic thickness) than was determined in previous studies, and Atkinson & Boore (2006) modelled the aleatory uncertainty in attenuation by normal distributions of the geometric-spreading coefficients pointing out that the variability considered is sufficient to model the net effects of uncertainty in all attenuation parameters (including Q factor in the inelastic attenuation) and that mapping all of the attenuation uncertainty into geometric is a simple way to approximate the expected overall behaviour.

To account for near-surface attenuation factor a hight cut filter is applied, P(f)=exp$(-\pi\ f\ k)$ – P(ω) in Eqn. 2.1- which describes the observed rapid spectral decay at high frequencies. Carvalho *et al.*,

(2009) inferred a value of k = 0.03 s from the analysis of the data set of acceleration records. This parameter was found to have impact on predicted amplitudes of ground motion so the aleatory uncertainty was modelled by a uniform distribution taking values between 0.015 and 0.04.

Median path and crustal parameters values assumed for the stochastic simulation are summarized in Table 2, together with variability (uncertainty) adopted for some of the parameters.

Table 2. Median path and crustal parameters and uncertainty

Parameter	Median value (mean)	Distribution type	Standard deviation	Min	Max
Shear wave velocity (km/s)	3.5				
Density (g/cm^3)	2.8				
Crustal thikness, D (km)	31				
Geometric spreading, R^b, coefficient b =	-1 (R < 1.5*D) 0 (1.5*D< R ≤ 2.5*D) -0.5 (R > 2.5*D)	normal	0.2		
Quality factor, Q	$250\ f^{0.7}$				
Kappa (s)	0.03	uniform		0.015	0.04

Results:
Simulations were performed using RSSIM, with median values of parameters presented in tables 1 and 2, including uncertainty, for a site at 20 km from the finite source. Note that as the segment of PRVF near the dam site is geographically known, together with the geographic coordinates of the site, both source and receiver are spatially represented.

15 random trials were realized, each run with a different combination of the set of parameters, according to the probabilistic distribution of each one, considering a random distribution of the slip and a random nucleation point so that it was possible to capture directivity effects. Results were presented in terms of response spectral amplitudes and time histories.

The 15 response spectra that resulted from this analysis are presented on the left hand side of Fig. 1. On the right hand side, the mean and the mean plus and minus one standard deviation spectra are shown.

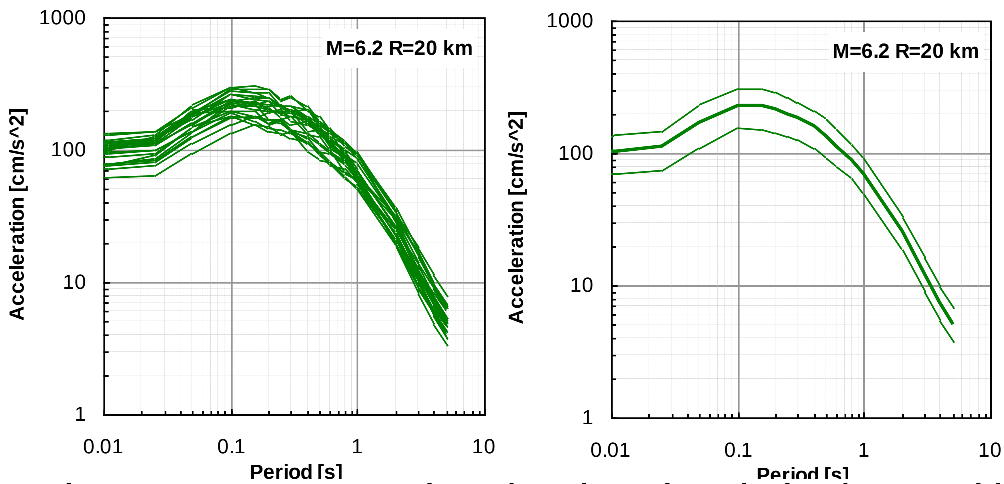

Figure 1. Left: 15 response spectra, corresponding to the random trials simulated. Right: mean and the mean plus and minus one standard deviation spectra.

Parallel to response spectra analysis, the same methodology and inputs were applied to obtain time histories. The RSSIM procedure routine was taken from EXSIM. First, the stochastic point source modelling is applied following Boore (2003): it is generated a windowed time series of band limited random white Gaussian noise with zero mean amplitude and unit variance. This series is transformed to the frequency domain; the spectrum is normalized by the square root of the mean square amplitude spectrum and is then multiplied by the desired Fourier amplitude spectrum as given by Eqn. 2.1. The resulting spectrum is Fourier transformed back to time domain to yield a stochastic time series. Extending this method to the finite fault, this time series is the motion from each sub-source and all time series are summed at the site with the proper time delay to generate the final motion at the observation point and consequently, to establish the proper time duration of the ground motion at the site.

4. CONCLUSION

Well-founded physical models must be used as the basis for the predictions of strong motion in Portugal. The finite-fault model, when a fault is known, will generate more accurate ground-motion time histories for a future earthquake at a site near the fault, since it incorporates average directivity effects and provides the correct ground motion based on fault rupture time. Being so, it is emphasized in this paper that the MCE should be synthesized by stochastic finite fault methods, as there are major obstacles when using seismic hazard commonly used approaches such as PSHA and DSHA.

The stochastic finite fault methodology was applied for the first time to assess MCE for some Portuguese dams.

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