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The uMkhomazi Water Project Phase 1: Module 1: Technical Feasibility Study: Raw Water

GEOTECHNICAL REPORT

SUPPORTING DOCUMENT 1:

PROBABILISTIC SEISMIC HAZARD ANALYSIS FOR SMITHFIELD DAM, LANGA BALANCING DAM AND THE CONVEYANCE SYSTEM

FINAL

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Author:	***A Kijko***
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CONSULTANTS: AECOM (BKS*) in association with AGES, MM&A and Urban-Econ.

Approved for ***Consultants****:*

A Kijko	***D Badenhorst***
Sub-Task Leader	*Task Leader*

DEPARTMENT OF WATER AFFAIRS (DWA): Directorate: Options Analysis

Approved for ***DWA****:*

K Bester	***LS Mabuda***
Chief Engineer: Options Analysis (East)	*Chief Director: Integrated Water Resource Planning*

* *BKS (Pty) Ltd was acquired by AECOM Technology Corporation on 1 November 2012*

Prepared by:

AECOM

AECOM SA (Pty) Ltd
PO Box 3173
Pretoria
0001

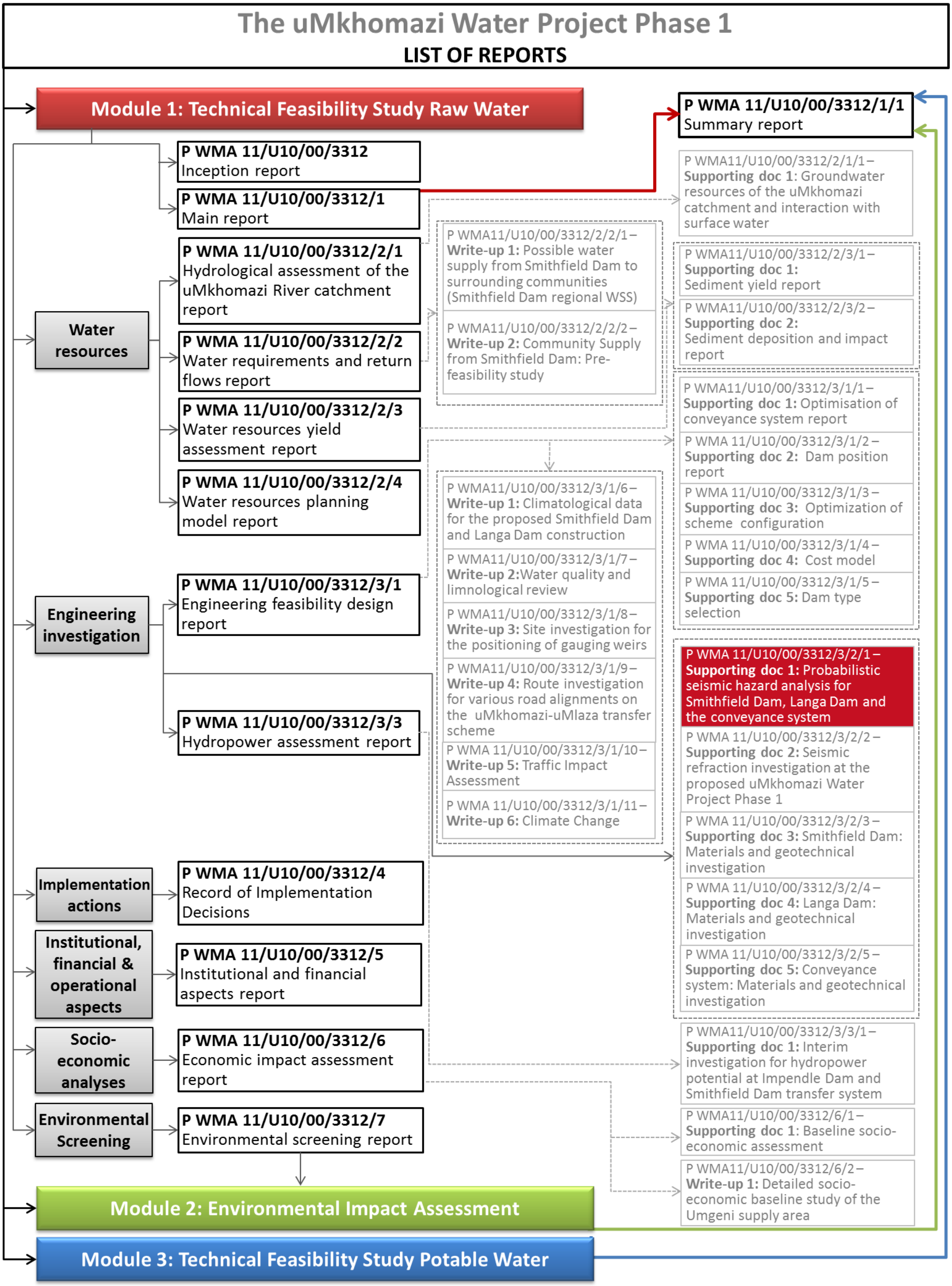
In association with:

Africa Geo-Environmental Services	**Mogoba Maphuthi and Associates**	**Urban-Econ**
AGES Purpose with Passion	Mogoba Maphuthi & Associates (MMA)	UE URBAN-ECON Development Economists

PREAMBLE

In June 2014, two years after the commencement of the uMkhomazi Water Project Phase 1 Feasibility Study, a new Department of Water and Sanitation was formed by Cabinet, including the formerly known Department of Water Affairs.

In order to maintain consistent reporting, all reports emanating from Module 1 of the study will be published under the Department of Water Affairs name.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Executive summary

A Probabilistic Seismic Hazard Analysis (PSHA) has been performed for the Smithfield Dam site, KwaZulu-Natal, South Africa. All earthquakes located within a radius of 320 km from the dam site were used in the assessment. The PSHA was performed using the Cornell-McGuire procedure which can be broken down into two phases: (1) spatial delineation of seismogenic sources within 320 km from the site and (2) integration of all possible earthquake scenarios from each source to obtain probabilities of exceedance of specified ground motion parameters.

The applied procedure requires knowledge of the regional geology, tectonics, paleo-historic and instrumentally recorded seismicity. The best available information from the public domain was provided by AECOM, Pretoria, but is unfortunately incomplete. The incompleteness of the seismotectonic model of the area contributes to the uncertainties of PSHA assessment.

All calculations are repeated twice, each for a different ground motion prediction equation (GMPE):

- *AB06 (Atkinson and Boore, 2006)*
- *BA08 (Boore and Atkinson, 2008).*

The first, AB06 GMPE, (Atkinson and Boore, 2006) was developed for the central and eastern United States which is situated in a type of tectonic environment known as an intraplate region, or equivalently, stable continental area. Because of the limited number of strong-motion records in the stable continental areas, the attenuation relation (horizontal component) has been developed mainly by help of stochastic modelling.

The second applied GMPE, denoted as BA08, (Boore and Atkinson, 2008) is appropriate for predicting the earthquake generated horizontal component of ground motions in active tectonic regions with shallow crustal seismicity. It was derived by empirical regression of a strong-motion database compiled by the "PEER NGA" (Pacific Earthquake Engineering Research Center's Next Generation Attenuation) project. For frequency of ground motion exceeding 1 Hz, the analysis used 1,574 records from 58 earthquakes in the distance range of 0 km to 400 km (Boore and Atkinson, 2008).

The PSHA was performed using conventional, Cornell-McGuire procedure (Cornell, 1968; McGuire, 1976; 1978), where the integration across the uncertainty in the peak ground acceleration PGA prediction equation is an integral part of the methodology.

In accordance to the current seismic regulations provided in Bulletin #72 by the International Committee for Large Dams, (ICOLD, 1989); Eurocode 8 (2004) and ASCE (2005), three seismic designed levels were considered: Operating Basis Earthquake (OBE), Maximum Design Earthquake (MDE) and Maximum Credible Earthquake (MCE).

The results of the PSHA are given in terms of mean return periods and probabilities of being exceeded for horizontal component of PGA.

Based on the logic tree formalism, the expected values of horizontal component of OBE, MDE and MCE for the site of Smithfield Dam site, KwaZulu-Natal are:

- *OBE (Return Period 144 years) = 0.016 g*
- *MDE (Return Period 475 years) = 0.021 g*
- *MCE (Return Period 10,000 years) = 0.113 g*

According to the applied guidelines, the site of the future dam is rated as low risk.

The uniform acceleration response spectra (horizontal component) are also provided.

A simple procedure for conversion of PSHA characteristics from horizontal to vertical component of PGA and spectra is described in Appendix G.

All results of calculations are based on the assumption that the dam structures are founded on rock (NEHRP site class B/C, or equivalently to shear velocity 670 m/sec, averaged over the upper 30m). If such an assumption is incorrect, results of the calculations must be corrected for the actual ground conditions. Appendix H describes in detail how such a correction can be implemented. Finally, Appendix I provides the fundamentals of a PSHA and its interpretation.

All quantitative assessments of seismic hazard done for site of the Smithfield Dam are applicable to all engineering structures which are located in a radius of up to ca. 50km from the site of the dam. The above statement must be verified, if in the vicinity of the structures there are tectonic active faults present, i.e. faults which are capable of generating seismic events.

The lack of the regional ground motion prediction equation, local seismotectonic model and information about seismic potential of faults in vicinity of the dam site, are the main sources of uncertainty in this PSHA assessment. The uncertainty can be reduced by incorporation of the results of the seismotectonic and geological investigations on the site.

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DEFINITION OF TERMS, SYMBOLS AND ABBREVIATIONS

Acceleration	The rate of change of particle velocity per unit time. Commonly expressed as a fraction or percentage of the acceleration due to gravity (g), where g = 9.81 m/s^2.
Acceleration Response Spectra (ARS)	Spectral acceleration is the movement experienced by a structure during an earthquake.
Annual Probability of Exceedance	The probability that a given level of seismic hazard (typically some measure of ground motions, e.g., seismic magnitude or intensity), or seismic risk (typically economic loss or casualties)
Area-specific mean seismic activity rate (λA)	Mean rate of seismicity for the whole selection area in the vicinity of the site for which the PSHA is performed.
Attenuation	A decrease in seismic-signal ***amplitude*** as waves propagate from the seismic source. Attenuation is caused by geometric spreading of seismic-wave energy and by the absorption and scattering of seismic energy in different earth materials.
Attenuation law - ground motion prediction equation (GMPE)	A mathematical expression that relates a ground motion parameter, such as the peak ground acceleration, to the source and propagation path parameters of an earthquake such as the magnitude, source-to-site distance, fault type, etc. Its coefficients are usually derived from statistical analysis of earthquake records. It is a common engineering term known as ground motion prediction equation (GMPE).
b-value (b)	A coefficient in the frequency-magnitude relation, log N(m) = a – bm, obtained by Gutenberg and Richter (1941; 1949), where m is the earthquake magnitude and N(m) is the number of earthquakes with magnitude greater than or equal to m. Estimated b-values for most seismic sources fall between 0,6 and 1,2.
Capable (active) fault	A mapped fault that is deemed a possible site for a future earthquake with magnitude greater than some specified threshold.
Catalogue (seismic events)	A chronological listing of earthquakes. Early catalogues were purely descriptive, i.e., they gave the date of each earthquake and some description of its effects. Modern catalogues are usually quantitative, i.e., earthquakes are listed as a set of numerical parameters describing origin time, hypocenter location, magnitude, focal mechanism, moment tensor, etc.
Design Earthquake	The postulated earthquake (commonly including a specification of the ***ground motion*** at a site) that is used for evaluating the earthquake resistance of a particular structure.
Elastic design spectrum (or spectra)	The specification of the required strength or capacity of the structure plotted as a function of the natural period or frequency of the structure appropriate to earthquake response at the required level. Design spectra are often composed of straight line segments (Newmark and Hall, 1982) and/or simple curves, for example, as in most building codes, but they can also be constructed from statistics of response spectra of a suite of ground motions appropriate to the design earthquake(s). To be implemented, the requirements of a design spectrum are associated with allowable levels of stresses, ductilities, displacements or other measures of response.
Earthquake	Ground shaking and radiated seismic energy caused most commonly by sudden slip on a fault, volcanic or magmatic activity, or other sudden stress

	changes in the Earth.
Epicentre	The epicentre is the point on the earth's surface vertically above the hypocenter (or focus).
Epicentral distance(Δ)	Distance from the site to the epicentre of an earthquake.
Fault	A fracture or fracture zone in the Earth along which the two sides have been displaced relative to one another parallel to the fracture. The accumulated displacement may range from a fraction of a meter to many kilometres. The type of fault is specified according to the direction of this slip. Sudden movement along a fault produces earthquakes. Slow movement produces a seismic creep.
Focal depth(h)	Focal depth is the vertical distance between the hypocentre and epicentre.
Frequency	The number of cycles of a periodic motion (such as the ground shaking up and down or back and forth during an earthquake) per unit time; the reciprocal of period. Hertz (Hz), the unit of frequency, is equal to the number of cycles per second.
Ground motion	The movement of the earth's surface from earthquakes or explosions. Ground motion is produced by waves that are generated by sudden slip on a fault or sudden pressure at the explosive source and travel through the earth and along its surface.
Ground motion parameter	A parameter characterizing ground motion, such as peak acceleration, peak velocity, and peak displacement (peak parameters) or ordinates of response spectra and Fourier spectra (spectral parameters).
Heterogeneity	A medium is heterogeneous when its physical properties change along the space coordinates. A critical parameter affecting seismic phenomena is the scale of heterogeneities as compared with the seismic wavelengths. For a relatively large wavelength, for example, an intrinsically isotropic medium with oriented heterogeneities may behave as a homogeneous anisotropic medium.
Hypocenter	The hypocenter is the point within the earth where an earthquake rupture starts. The epicentre is the point directly above it at the surface of the Earth. Also commonly termed the focus.
Hypocentral distance (r)	Distance from the site to the hypocenter of an earthquake.
Induced earthquake	An earthquake that results from changes in crustal stress and/or strength due to man-made sources (e.g., underground mining and filling of a water reservoir), or natural sources (e.g., the fault slip of a major earthquake). As defined less rigorously, “induced” is used interchangeably with “triggered” and applies to any earthquake associated with a stress change, large or small.
Local Magnitude (ML)	A magnitude scale introduced by Richter (1935) for earthquakes in southern California. ML was originally defined as the logarithm of the maximum amplitude of seismic waves on a seismogram written by the Wood-Anderson seismograph (Anderson and Wood, 1925) at a distance of 100 km from the epicentre. In practice, measurements are reduced to the standard distance of 100 km by a calibrating function established empirically. Because Wood-Anderson seismographs have been out of use since the 1970s, ML is now computed with simulated Wood-Anderson records or by some more practical methods.
Magnitude	In seismology, a quantity intended to measure the size of earthquake and is independent of the place of observation. Richter magnitude or local magnitude (ML) was originally defined in Richter (1935) as the logarithm of the maximum amplitude in micrometers of seismic waves in a seismogram written by a standard Wood-Anderson seismograph at a distance of 100 km from the epicentre. Empirical tables were constructed to reduce

	measurements to the standard distance of 100 km, and the zero of the scale was fixed arbitrarily to fit the smallest earthquake then recorded. The concept was extended later to construct magnitude scales based on other data, resulting in many types of magnitudes, such as body-wave magnitude (mb), surface-wave magnitude (MS), and moment magnitude (MW). In some cases, magnitudes are estimated from seismic intensity data, tsunami data, or duration of coda waves. The word "magnitude" or the symbol M, without a subscript, is sometimes used when the specific type of magnitude is clear from the context, or is not really important.
Maximum Regional Earthquake Magnitude (M_{max})	Upper limit of magnitude for a given seismogenic zone or entire region. Often also referred to as the maximum credible earthquake (MCE).
NEHRP	National Earthquake Hazards Reduction Program. For details see www.femalaw.cm/glossary.php
Operating Basis Event (OBE)	Event with an average return period in the order of 145 years i.e. 50 % probability of exceedance in 100 years.
Oscillator	In earthquake engineering, an oscillator is an idealized mass-spring system used as a model of the response of a structure to earthquake ground motion. A seismograph is also an oscillator of this type
Peak Ground Acceleration (PGA)	The maximum acceleration amplitude measured (or expected) of an earthquake.
Probabilistic Seismic Hazard Analysis (PSHA)	Available information on earthquake sources in a given region is combined with theoretical and empirical relations among earthquake magnitude, distance from the source and local site conditions to evaluate the exceedance probability of a certain ground motion parameter, such as the peak acceleration, at a given site during a prescribed period.
Response spectrum	The response of the structure to a specified acceleration time series of a set of single-degree-of-freedom oscillators with chosen levels of viscous damping, plotted as a function of the undamped natural period or undamped natural frequency of the system. The response spectrum is used for the prediction of the earthquake response of buildings or other structures.
Seismic Hazard	Any physical phenomena associated with an earthquake (e.g., ground motion, ground failure, liquefaction, and tsunami) and their effects on land use, man-made structure and socio-economic systems that have the potential to produce a loss. It is also used without regard to a loss to indicate the probable level of ground shaking occurring at a given point within a certain period of time.
Seismic Wave	A general term for waves generated by earthquakes or explosions. There are many types of seismic waves. The principle ones are body waves, surface waves, and coda waves.
Seismic zone	An area of seismicity probably sharing a common cause.
Seismogenic	Capable of generating earthquakes.
Site-specific mean activity rate (λ)	Mean activity rate of the selected ground motion parameter experienced at the site.
Strong ground motion	A ground motion having the potential to cause significant risk to a structure's architectural or structural components, or to its contents. One common practical designation of strong ground motion is a peak ground acceleration (PGA) of 0.05g or larger.
GMPE	Ground motion prediction equation

1 Scope of Work

The Natural Hazard Assessment Consultancy (NHAC) Centurion, was requested by BKS Group (Pty) Ltd (BKS, now AECOM), Hatfield, PO Box 3173, Pretoria 0001, Gauteng, South Africa *Reg. No: 1996/009249/07)*, (BKS Professional Services Work Order of 1 December 2011), to provide a probabilistic seismic hazard analysis (PSHA) for the site of the Smithfield Dam, KwaZulu-Natal, South Africa, having approximate coordinates latitude 29^0 46'30.31" S and longitude 29^0 56' 39.43" E.

In general, the hazardous effects of earthquakes can be divided into three categories:

- Those resulting directly from a certain level of ground shaking
- Those at the site resulting from surface faulting or deformations
- Those triggered or activated by a certain level of ground shaking such as the generation of a tsunami or landslide.

This study covers Category 1 only and in case of PSHA is limited to the following investigations:

- Selection of earthquakes within a radius of 320 km from the site.
- Assessment of earthquake recurrence parameters for the area.
- Discussion on applicable ground motion prediction equations (GMPEs) used in this study.
- PSHA calculations and provision of seismic hazard curves in terms of Peak Ground Acceleration (PGA) and Uniform (acceleration) Response Spectra (URS).
- PGA calculation for the Operating Basis Earthquake (OBE), Maximum Design Earthquake (MDE) and the Maximum Credible Earthquake (MCE). In this report, the OBE is defined as PGA having return period of 144 years or equivalently having a 50% probability of exceedance in 100 years. The MCE is suggested as PGA having return period of 10,000 years. In addition, following e.g. regulation *ER No. 1110-2-1806, (1995)*, *Eurocode 8 (2004)*, or *ASCE 7-05 (2005)*, the MDE is calculated as PGA having a return period of 475 years or equivalently having a 10% probability of exceedance in 50 years.

The classic *Newmark and Hall (1982)* elastic design spectra for 5% damping anchored at the OBE, MDE and MCE values.

The PSHA was performed using conventional, Cornell-McGuire procedure (*Cornell, 1968; McGuire, 1976; 1978*), where the integration across the uncertainty in the ground motion prediction equation is an integral part of the methodology.

The procedure used in this seismic hazard assessment consists of two steps. The first step is applicable to seismic sources (known also as seismogenic sources or seismic zones) in the vicinity of the site, for which the seismic hazard analysis is required. The procedure requires an estimation of the seismic source parameters. The second step is applicable to a specified site, and consists of assessing the site-specific parameters, which describe the amplitude distribution of ground motion parameter PGA.

The PGA is the maximum acceleration of the ground shaking during an earthquake. Spectral acceleration is the movement experienced by a structure during an earthquake. The acceleration is expressed in units of gravity, g, which is equal to 9.81 m/s^2.

Lists of all seismic events used in the study are given in **Appendix A**. The procedure for PSHA as applied in this work is described in **Appendix B**. Lists of seismic hazard occurrence parameters are given in **Appendix C**. **Appendix D** provides information on the applied GMPEs. **Appendices E-F** shows the results of the PSHA calculations for the site of the dam. It contains details of the computations, input data, respective hazard characteristics and their uncertainties.

The results are given in terms of mean return periods and probabilities of being exceeded for specified values of horizontal component of PGA. Simple procedure of conversion of the above results from the horizontal to the vertical component of PGA is described in the paper by *Abrahamson and Litehiser*, **Appendix G**.

All results of calculations are based on the assumption that the wind farm structures are founded on rock (NEHRP site class B, or equivalently to shear velocity 670 m/sec, averaged over the upper 30m). If such an assumption is incorrect, results of the calculations must be corrected for the actual ground conditions. **Appendix H** describes in details how such corrections can be implemented. Finally, **Appendix I** provides the fundamentals of a PSHA and its interpretation.

2 INTRODUCTION

The Natural Hazard Assessment Consultancy (NHAC) Centurion, was requested by BKS Group (Pty) Ltd (BKS, now AECOM), Hatfield, PO Box 3173, Pretoria 0001, Gauteng, South Africa *Reg. No: 1996/009249/07)*, (BKS Professional Services Work Order of 1 December 2011), to provide a probabilistic seismic hazard analysis (PSHA) for the site of the Smithfield Dam, KwaZulu-Natal, South Africa, having approximate coordinates latitude 29^0 46'30.31" S and longitude 29^0 56' 39.43" E.

- The objective of a PSHA is to obtain the probabilities of the occurrence of seismic events of a specified size in a given time interval. The methodology used in most PSHA was first defined by Cornell (1968). There are four basic steps in a PSHA:
- Step 1 is the definition of seismotectonic sources. Sources may range from small faults to large seismotectonic provinces.
- Step 2 is the definition of earthquake parameters for each source, where each source is defined by an earthquake probability distribution or earthquake recurrence relationship. A recurrence relationship indicates the chance of an earthquake of a given size occurring anywhere inside the source during a specified period. An upper bound for the earthquakes for each source is chosen, which represents the source characteristic, maximum possible earthquake magnitude.
- Step 3 is the estimation of the earthquake effects, using several GMPEs, each relating a ground motion parameter, such as PGA with distance and earthquake magnitude.
- Step 4 is the determination of the hazard at the site. The effects of all earthquakes of different sizes occurring at different locations in different earthquake sources at different probabilities of exceedance are integrated into one hazard curve that shows the probability of exceeding different levels of ground motion (such as PGA) at the site during a specified period of time.

The PSHA was performed using the conventional, Cornell-McGuire procedure (*Cornell, 1968; McGuire, 1976; 1978*), where the integration across the uncertainty in the ground motion prediction equation is an integral part of the methodology.

3 SEISMIC SOURCES AND THEIR PARAMETERS

Figure 3.1 shows the distribution of all known seismic events with magnitude M_W = 3.0 and stronger, that occurred within a radius of 320 km from the future dam site. Only the largest events within a radius of 320 km from the dam site were used in the analysis, as only these events can be considered to contribute to the seismic hazard at the dam site. Events at larger distances from the structure are not likely to generate PGA's large enough to be of engineering concern.

The seismic event catalogue used in this study was compiled from several sources. After critical analysis of each of the data sources, the main contribution to pre-instrumentally recorded seismicity come from *Brandt et al. (2005)*. The instrumentally recorded events are mainly selected from databases provided by the International Seismological Centre in UK.

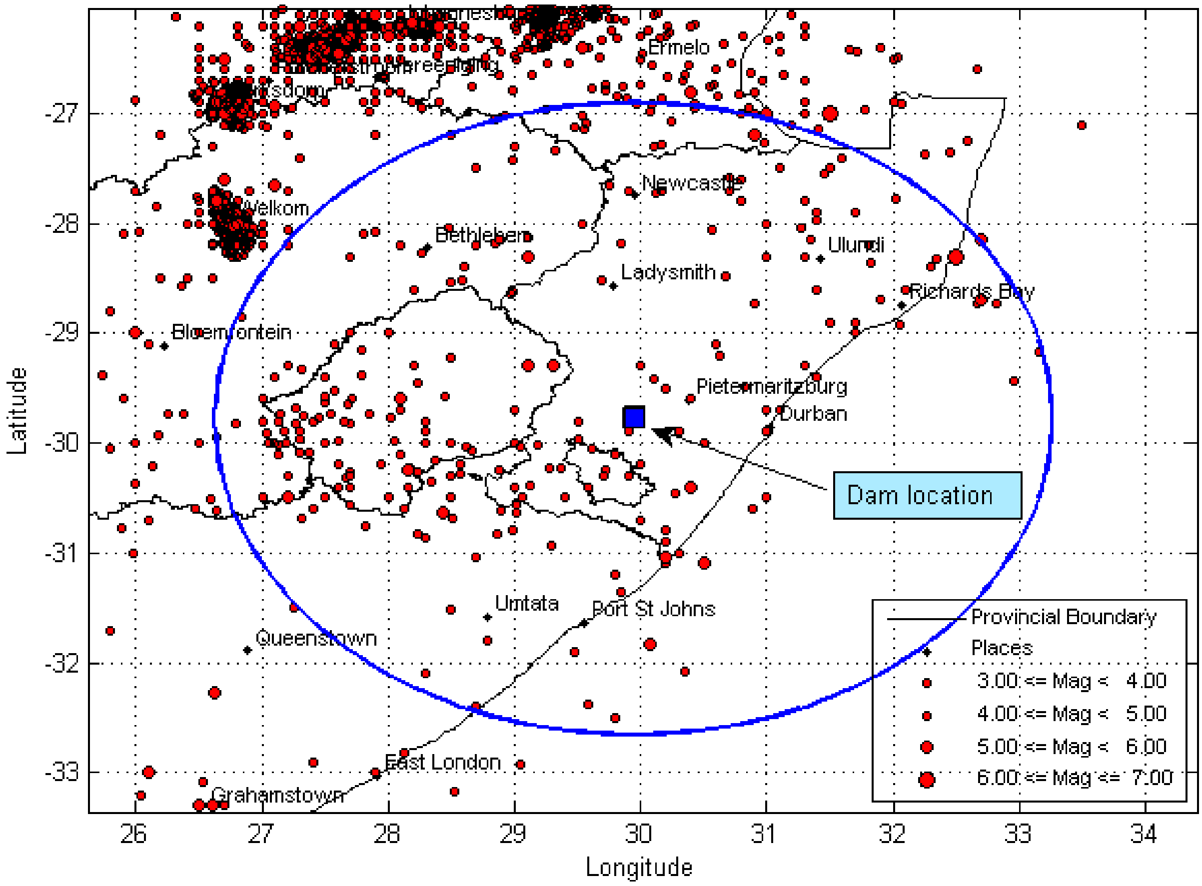

Figure 3.1: Distribution of the largest seismic events within 320 km radius of the Smithfield Dam used in the study. The future location of the dam site is shown as a blue square.

It is assumed that magnitudes of earthquakes recorded within the specified area are distributed according to the Gutenberg-Richter relation

$$\log n(m) = a - b \cdot m, \qquad \textbf{(6.1)}$$

Where *a* is a constant, *b* refers to the slope of the line, *m* is the earthquake magnitude and *n* the cumulative number of earthquakes occurring annually within a magnitude interval <*m*, *m* +Δ *m*>, or the number of earthquakes equal or larger than *m*. The parameter *a* is the *measure of the level of seismicity*, whereas the parameter *b*, which is typically close to 1, describes the *ratio* between number of small and large magnitude events.

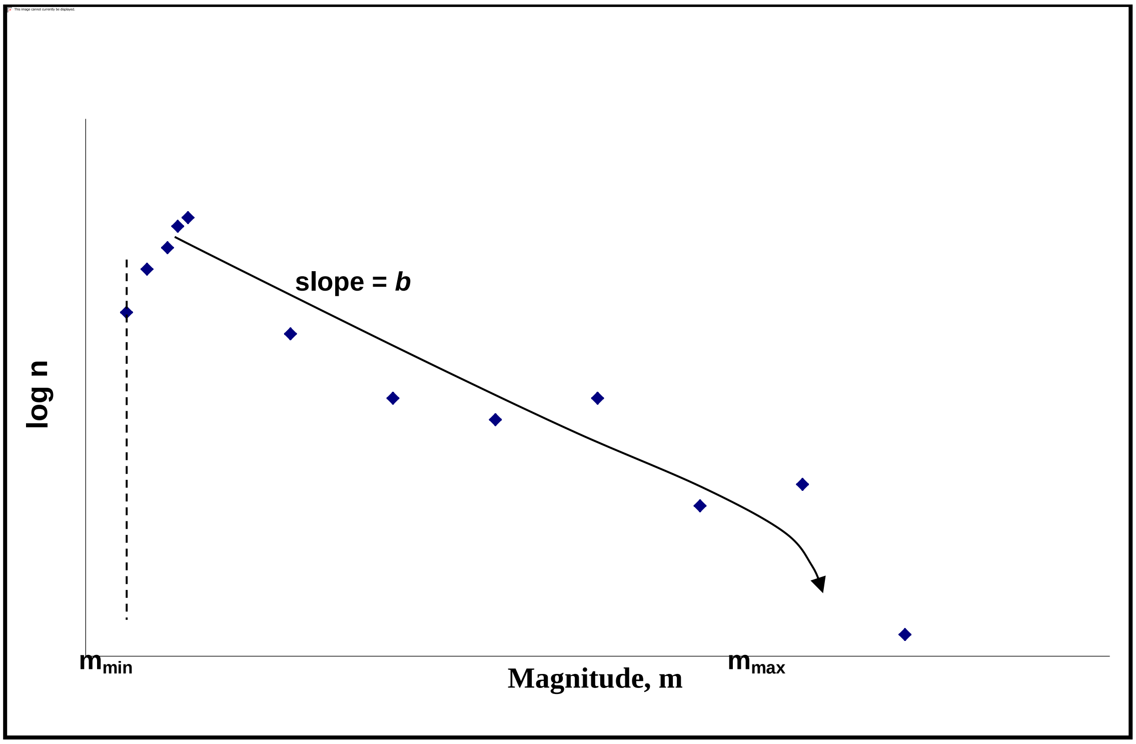

Figure 3.2: Schematic illustration of the double truncated frequency-magnitude Gutenberg-Richter relation. The slope of the curve is described by parameter b, known as the b-value of the Gutenberg-Richter. Value m_{min} is the minimum earthquake magnitude to be considered and m_{max} is the regional characteristic, maximum possible earthquake magnitude.

Acceptance of the classic frequency-magnitude Gutenberg-Richter relation (6.1) is equivalent to the assumption that the cumulative distribution function (CDF) of earthquake magnitude distribution is of the form

$$F_M(m) = \frac{\exp(-\beta m_{\min}) - \exp(-\beta m)}{\exp(-\beta m_{\min}) - \exp(-\beta m_{\max})} \quad (6.2)$$

In Figure 3.2 and equation (6.2), m_{min} is the minimum earthquake magnitude for which the earthquake catalogue is considered complete, m_{max} is the maximum possible earthquake magnitude, and $\beta = b$ ln10, where b is the parameter of the Gutenberg-Richter magnitude-frequency relation (6.1).

Following *Cornell (1968)*, each seismic source is described by three parameters: the mean seismic activity rate λ, Gutenberg-Richter *b*-value, and m_{max}.

The mean seismic activity rate λ , is defined as the ratio

$$\lambda = \frac{Number\ of\ earthquakes\ with\ m \geq m_{\min}}{Time\ span\ of\ observations} \tag{6.3}$$

or equivalently as

$$\lambda = \frac{n(m \geq m_{\min})}{t}$$

Where *n* is the number of earthquakes of magnitude $m_{\min}$ and greater that occurred within a specified time interval *t.*

One can show that parameters *a* and *b,* level of completeness $m_{\min}$ and the mean activity rate λ, are linked together, and the following equation holds

$$a = \log_{10} \lambda + b \cdot m_{\min} \tag{6.4}$$

Following the respective guidelines, the first action required in the determination of PSHA is the generation of a ***data-driven*** seismotectonic model that divides the investigated region into areas of similar seismic potential, called ***seismogenic zones***. The first attempt to create the seismotectonic model for South Africa was done independently by *Du Plessis (1996)*, *Partridge (1995)* and *Hartnady (1996)*. The most recent attempt to develop a seismotectonic model for South Africa is described in two papers by *Singh et al. (2009; 2011)*. Unfortunately, all above attempts to build such a model have significant shortcomings and can be treated only as models of first-order and are not used in this study. In this report an alternative approach, as applied in the construction of the seismic hazard map for the United States (*Frankel et al., 1996, 2002*), has been used.

For the site, the area of 320 km radius was divided into 25km x 25km 'point seismic sources'. Then, for each point seismic source the parameters λ , *b*-value and m_{max} were calculated. The parameters of the three seismogenic zones, delineated by seismicity and the faults within the radius of 320 km of the dam site (**Figure 3.1**), were calculated separately and are provided in **Appendix C**.

In this investigation the recurrence parameters: the mean activity rate λ, *b*-value of Gutenberg-Richter and seismic source characteristic m_{max} are calculated according to maximum likelihood procedure developed *Kijko and Sellevoll (1992)* and *Kijko (2004)*. The applied approach accounts for incompleteness and uncertainty in the seismic event catalogues. More details can be found in the description of the applied methodology in **Appendix B**.

Reports of seismic phenomena in South Africa go back as far as 1620, to the early Dutch settlers. The seismicity is typically that of an intra-plate region. The natural seismic regime of a region of this type is characterised by a low-level activity by world standards, with earthquakes randomly distributed in space and time. The correlation between most of the earthquakes and the surface expression of major geological features is not clear (*Fernandez and Guzman, 1979, Brandt et al., 2005*).

Seismic events resulting from the deep-mining operations in the gold fields of the Gauteng, Klerksdorp and Welkom, form the majority of the seismic events recorded by the regional network of seismic stations. Usually, the depth of these events varies in the range of 2-3 km below the surface.

The database of seismic events for South Africa is incomplete, due to the fact that large parts of the area were very sparsely populated and the detection capabilities of the seismic network are far from uniform.

Following extensive analysis of the earthquake database it was established that the catalogue of the tectonic origin earthquakes can be divided into 8 parts, each with different level of completeness (**Table 3.1**).

Table 3.1: Division of the catalogue used in the analysis

Subcatoloque number	Level of completeness (M_w)	Beginning of the subcatologue	End of subcatalogue
1	5.9	1806/01/01	1905/12/31
2	5.3	1906/01/01	1909/12/31
3	4.9	1910/01/01	1949/12/31
4	4.6	1950/01/01	1970/12/31
5	4.0	1971/01/01	1980/12/31
6	3.8	1981/01/01	1990/12/31
7	3.5	1991/01/01	2002/12/31
8	3.3	2003/01/01	2010/12/31

Unfortunately, current geological knowledge of the area does not provide information on potential faults and their movement during the recent (quaternary) geological past, especially during last 35,000 years. No relationships between instrumentally recorded or historic seismicity and fault locations could be established. Also, no information on paleo-seismicity of the area was available. Therefore, in this report, the assessment of the maximum possible earthquake magnitude m_{max}, is based only on available information about seismicity of the area. The other two hazard recurrence parameters (the Gutenberg-Richter *b*-value and the mean activity rate λ) for each seismic source has been estimated according to procedure developed by *Kijko and Sellevoll (1992)*.

Seismic characteristics of the point seismic sources are given in **Appendix C**.

4 GROUND MOTION PREDICTION EQUATIONS (GMPES)

Attenuation is the reduction in amplitude or energy of seismic waves caused by the physical characteristics of the transmitting media or system. It usually includes geometric effects such as the decrease in amplitude of a wave with increasing distance from the source.

Attenuation relationships known as ground motion prediction equations (GMPEs) for the investigated area established on the basis of strong motion data are practically non-existent (*Minzi et al., 1999*). Three attempts to establish the horizontal component of PGA attenuation for the Eastern and Southern Africa are published: one by *Jonathan (1996)*, one by *Twesigomwe (1997)* and more recently by *Mavonga (2007)*. Jonathan's GMPE is based on the random vibration theory and is scaled by seismic records recorded by local seismic stations. Twesigomwe's equation is a modification of GMPE by *Krinitzky et al. (1988)*. Comparison of the two regional GMPE with the e.g. global equation by *Joyner and Boore (1988)*, *Boore et al., (1993; 1994)* shows relatively good agreement between regional attenuations and used globally. Finally, the most recent GMPE by *Mavonga (2007)* is based on well-known procedure (*Frankel, 1995; Irikura, 1986*) of simulation of the ground motion of large earthquakes using recordings of small earthquakes. Seismic records of small earthquakes adjacent to the expected large earthquakes have been treated as an empirical Green's function. The advantage of the procedure is that predicted ground motion contain information on the site response, details of path effects, etc., therefore often they can produce realistic time histories. Unfortunately, all three GMPEs are derived only for PGA, and are not applicable to short, below 10 km distances.

The lack of reliable regional GMPE is without doubt one of the biggest sources of uncertainty in this seismic hazard assessment.

In this study, all assessments of seismic hazard are based on two, recent and well-studied models of ground motion prediction equations.

The first applied GMPE of horizontal component (*Atkinson and Boore, 2006*), was developed for the central and eastern United States which is situated in a type of tectonic environment known as an intraplate region, or equivalently, stable continental area. The GMPE is denoted as AB06.

The second GMPE, belonging to the family of "Next Generation Attenuation" equations (NGA), (*Boore and Atkinson, 2008*), is appropriate for predicting earthquake generated horizontal component of ground motions in active tectonic regions with shallow crustal seismicity. It was derived by empirical regression of strong-motion database compiled by the "PEER NGA" (Pacific Earthquake Engineering Research Center's Next Generation Attenuation) project. For frequency of ground motion exceeding 1 Hz, the analysis used 1,574 records from 58 earthquakes in the distance range from 0 km to 400 km (*Boore and Atkinson, 2008*). The GMPE is denoted as BA08.

The two selected GMPEs, including their functional form and respective coefficients, are provided in **Appendix D**.

5 RESULTS OF THE PROBABILISTIC SEISMIC HAZARD ANALYSIS FOR THE SMITHFIELD DAM, KWAZULU-NATAL, SOUTH AFRICA

In order to determine the seismic hazard curve for the site, i.e. probabilities of exceedance of specified values of PGA, the earthquake recurrence parameters obtained for each seismic source, together with the applied GMPEs are integrated. Details of the applied procedure are described in **Appendix B**.

The respective seismic hazard curves (the annual probabilities of exceedance of median value of the PGA at the site) for the two considered GMPEs, AB06 and BA08, are shown in **Figure 5.1** and **Figure 5.2**. **Figure 5.3** and **Figure 5.4** show the associated, respective return periods of specified values of median PGA.

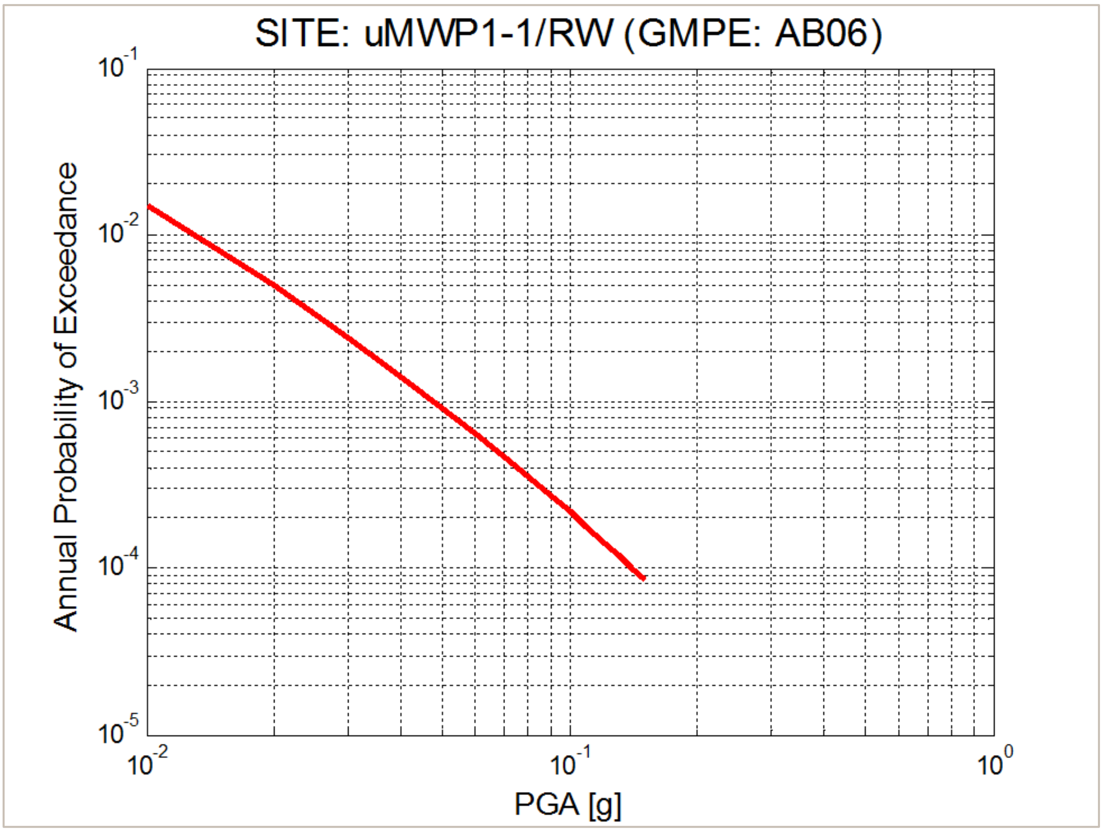

Figure 5.1: Annual probability of exceedance of median value of horizontal PGA at the site of the dam. Ground motion prediction equation: AB06 (Atkinson and Boore, 2006).

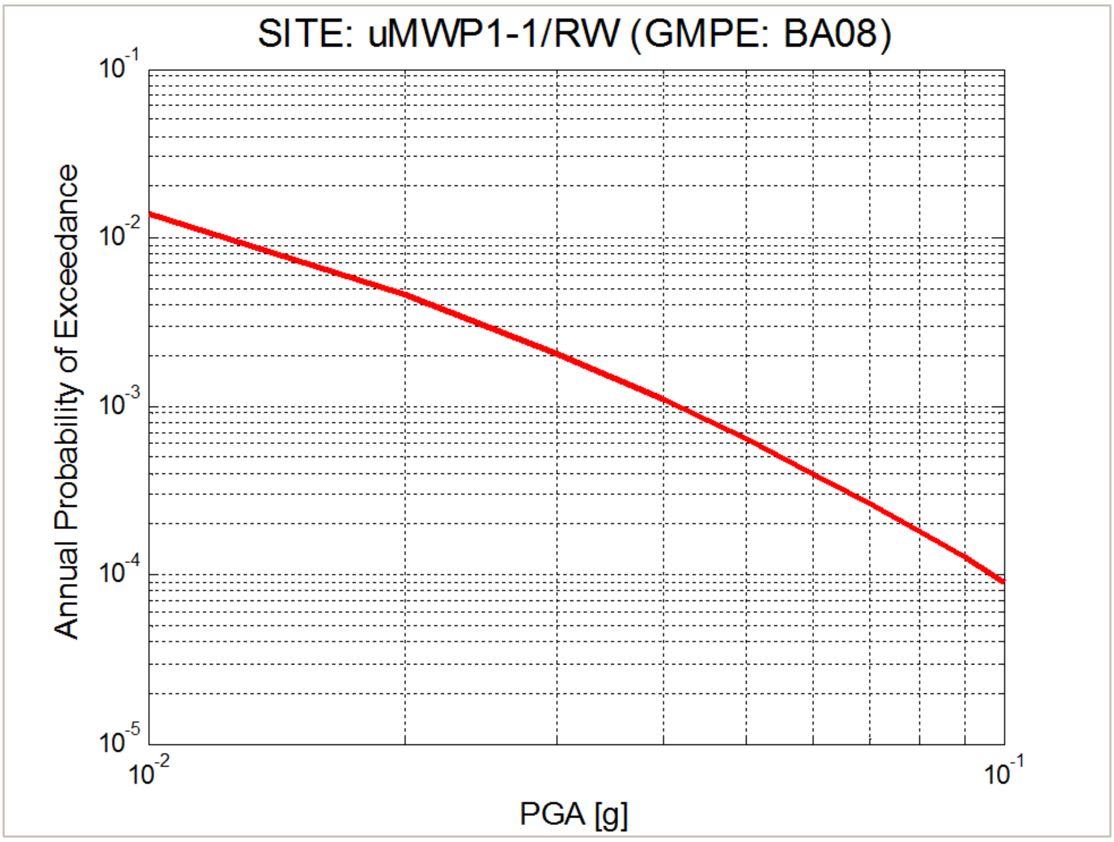

Figure 5.2: Annual probability of exceedance of median value of horizontal PGA at the site of the dam. Ground motion prediction equation: BA08 (Boore and Atkinson, 2008).

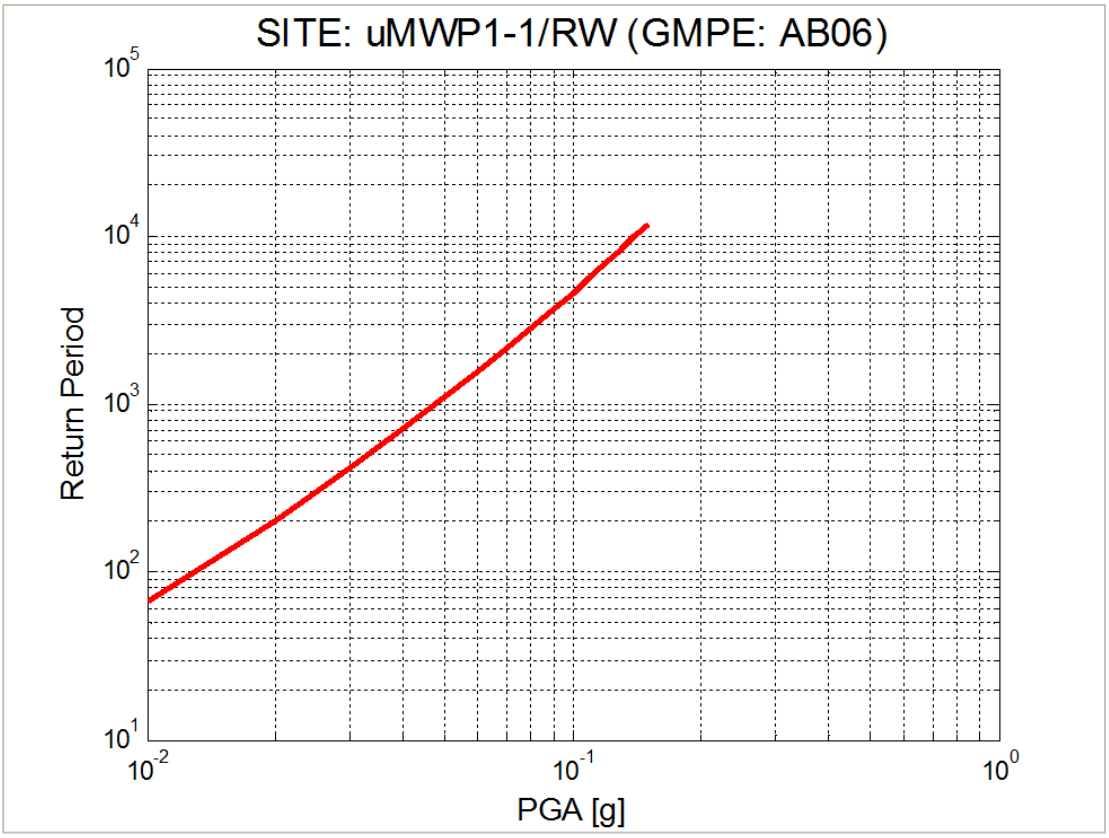

Figure 5.3: Mean return period of median value of horizontal PGA at the site of the dam. Ground motion prediction equation: AB06 (Atkinson and Boore, 2006).

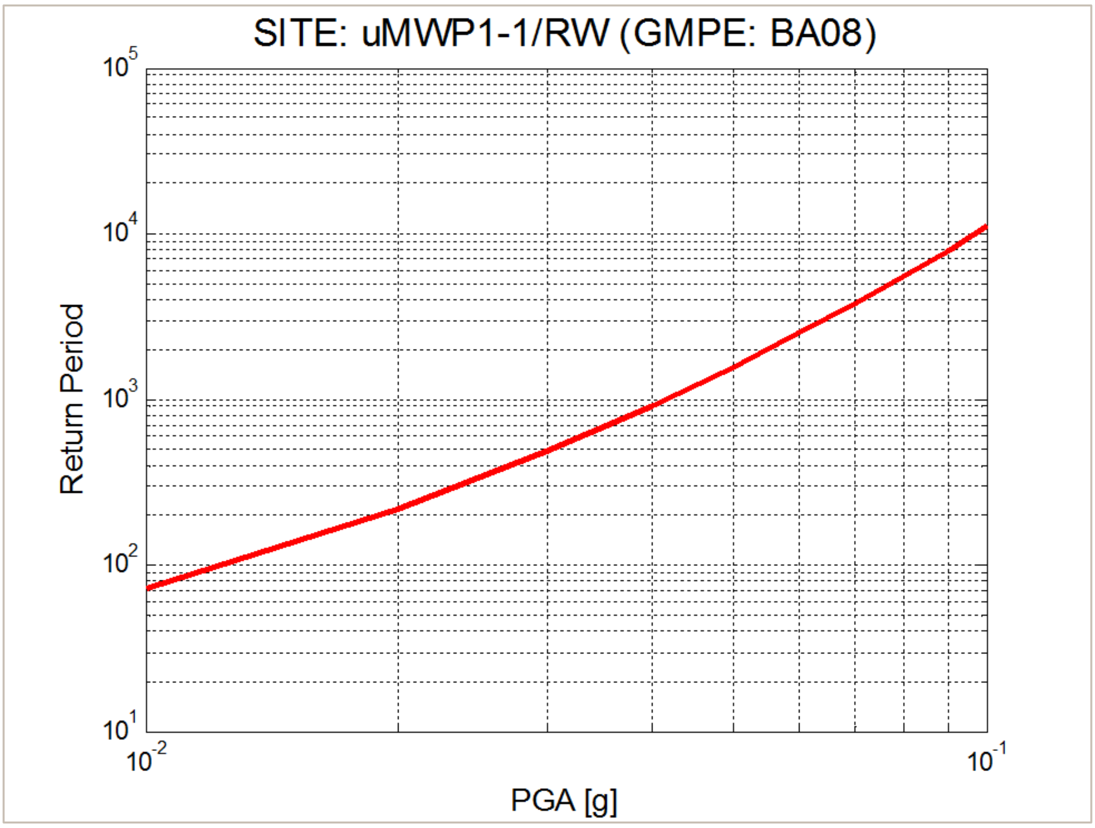

Figure 5.4: Mean return period of median value of horizontal PGA at the site of the dam. Ground motion prediction equation: BA08 (Boore and Atkinson, 2008).

All above results are also listed in the **Appendix E**. Plots of the same hazard curves and return periods, including their confidence intervals are shown in **Appendix F**. Simple conversion procedure of above results from horizontal to vertical component of PGA is described in **Appendix G**.

5.1 Maximum Credible Earthquake (MCE), Maximum Design Earthquake (MDE) and Operating Basis Earthquake (OBE)

Following the BKS (Pty) Ltd (now AECOM) request, three levels of ground motion at the dam site are considered, OBE, MDE and MCE.

The ***Operating Basis Earthquake (OBE)*** represents the level of ground motion at the dam site at which only minor damage is acceptable. The dam operation should remain functional and damage easily is repairable from the occurrence of earthquake shaking not exceeding the OBE (*ICOLD, 1989; Engineering and Design, ER 1110, 1995*). The quoted documents specifies that for civil works projects like the Smithfield Dam, one could use for the OBE a 50% probability of not being exceeded in 100 years, or equivalently, PGA with return period of 144 years.

The ***Maximum Design Earthquake (MDE)*** is the maximum level of ground motion for which a structure is designed. The associated performance requirement is that the structure performs without catastrophic failure, although severe damage or economic loss may be tolerated. For critical structures, the MDE is the same as the MCE. For all other structures, the MDE can be selected lower than the MCE (*Engineering and Design, ER 1110-2-1806; 1995*). In this report MDE is defined as earthquake with a return period of 475 years, or equivalently as PGA with 10% probability of exceedance within 50 years.

The ***Maximum Credible Earthquake (MCE)*** is the largest conceivable earthquake that appears possible along a recognized fault or within a geographically defined tectonic province, under the presently known or presumed tectonic framework. In this report MCE is defined, as the PGA having a return period of 10,000 years, or equivalently, 0.5% probability of exceedance in 50 years. The selected time period of 10,000 years is standard for critical structures for areas with low to moderate seismicity, *ICOLD (1989)*; *Engineering and Design, ER 1110-2-1806 (1995)*.

Table 5.1 lists the OBE, MDE and MCE estimates for two applied GMPEs. The OBE value for the two GMPEs is within range 0.015g – 0.016g. The MDE values fall within range 0.018g - 0.024g and MCE values fall within range of 0.090g to 0.137g.

Table 5.1: SSE, OBE, MDE and MCE estimates (horizontal component) for two considered GMPEs

	Return Period [y]	PGA [g] GMPE AB06	PGA [g] GMPE AB08
OBE	Return period of 144 years (equivalent to 50% probability of exceedance in 100 years)	0.016	0.015
MDE	Return period of 475 years (equivalent to 10% probability of exceedance in 50 years)	0.024	0.018
MCE	Return period of 10 000 years (equivalent to 0.5% probability of exceedance in 50 years)	0.137	0.090

According to the applied guidelines, the site of the future dam is rated as low risk.

One have to note, that the ICOLD guideline define one more parameter characterizing the dam associated seismic hazard, the ***Reservoir-Induced Earthquake (RIE)***. The REI is defined as the maximum level of ground motion, capable of being triggered at the dam site by the filling, drawdown or the presence of the reservoir. The value of REI depends on the dam location and local seismotectonic conditions, the RIE can be less than, equal to, or greater than the OBE. In any case, the RIE is less than the MDE.

5.2 NEWMARK-HALL ELASTIC RESPONSE SPECTRA

The elastic design response spectra provides a basis for computing design displacements and forces in systems expected to remain elastic during earth shaking.

Horizontal, 5% damping elastic design spectra were calculated by application of the *Newmark and Hall (1982)* procedure. The spectra are shown in **Figure 5.5** and **Figure 5.6**. The spectra are anchored at the OBE, MDE and MCE values of PGA respectively. Finally, **Figure 5.7** shows Newmark-Hall elastic design spectra anchored at the OBE, MDE and MCE values of PGA, estimated by the application of a logic tree procedure.

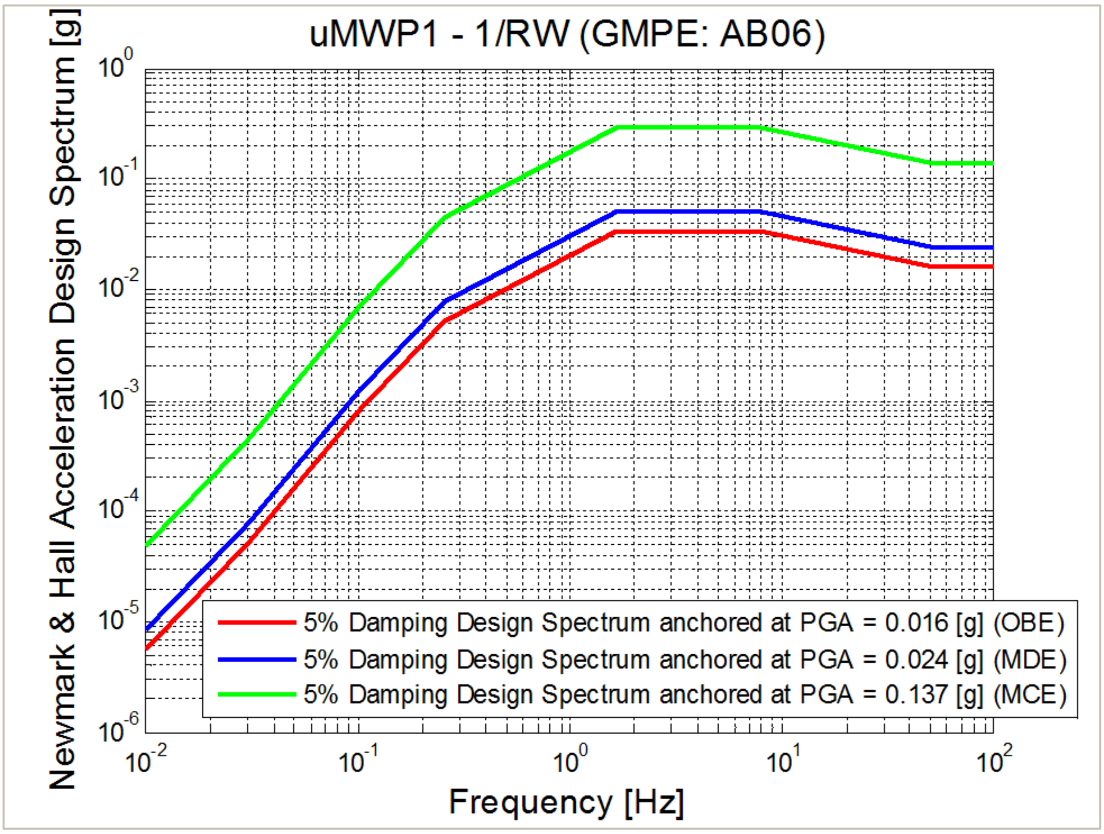

Figure 5.5: Newmark-Hall elastic design spectra anchored at the OBE, MDE and MCE values of horizontal PGA, calculated for ground motion prediction equation AB06 (Atkinson and Boore, 2006).

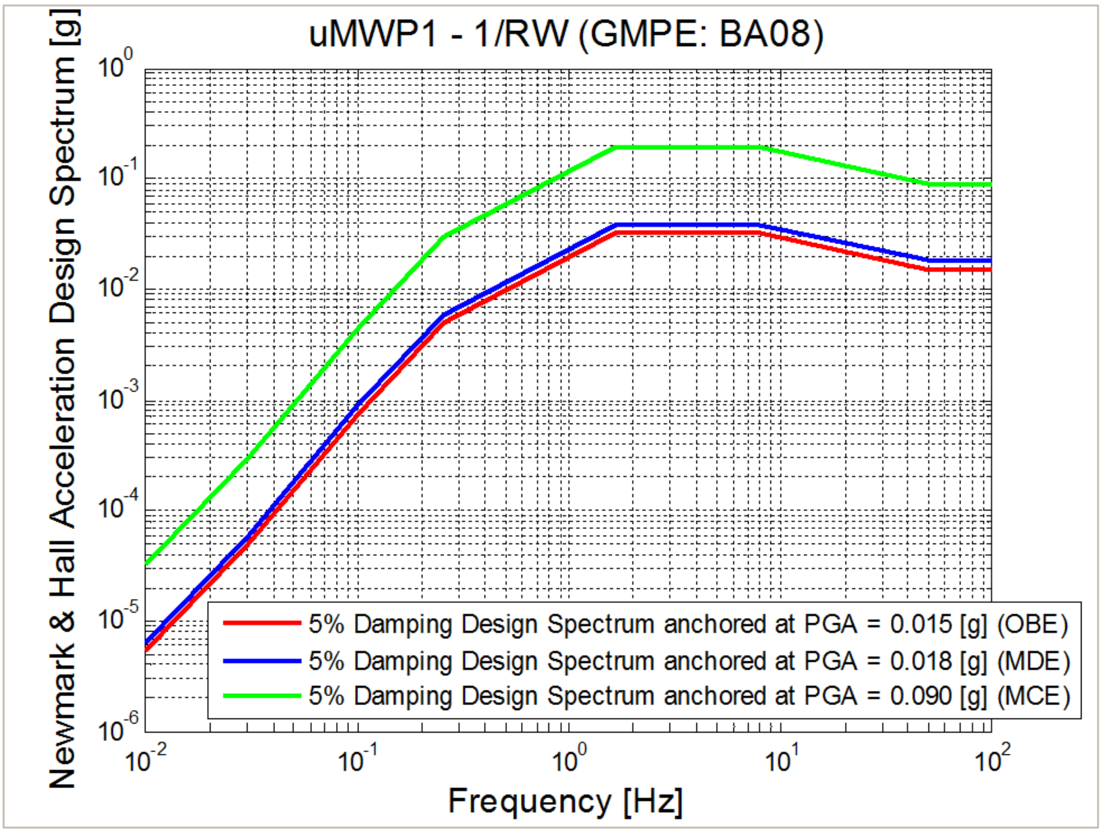

Figure 5.6: Newmark-Hall elastic design spectra anchored at the OBE, MDE and MCE values of horizontal PGA, calculated for ground motion prediction equation BA08 (Boore and Atkinson, 2008).

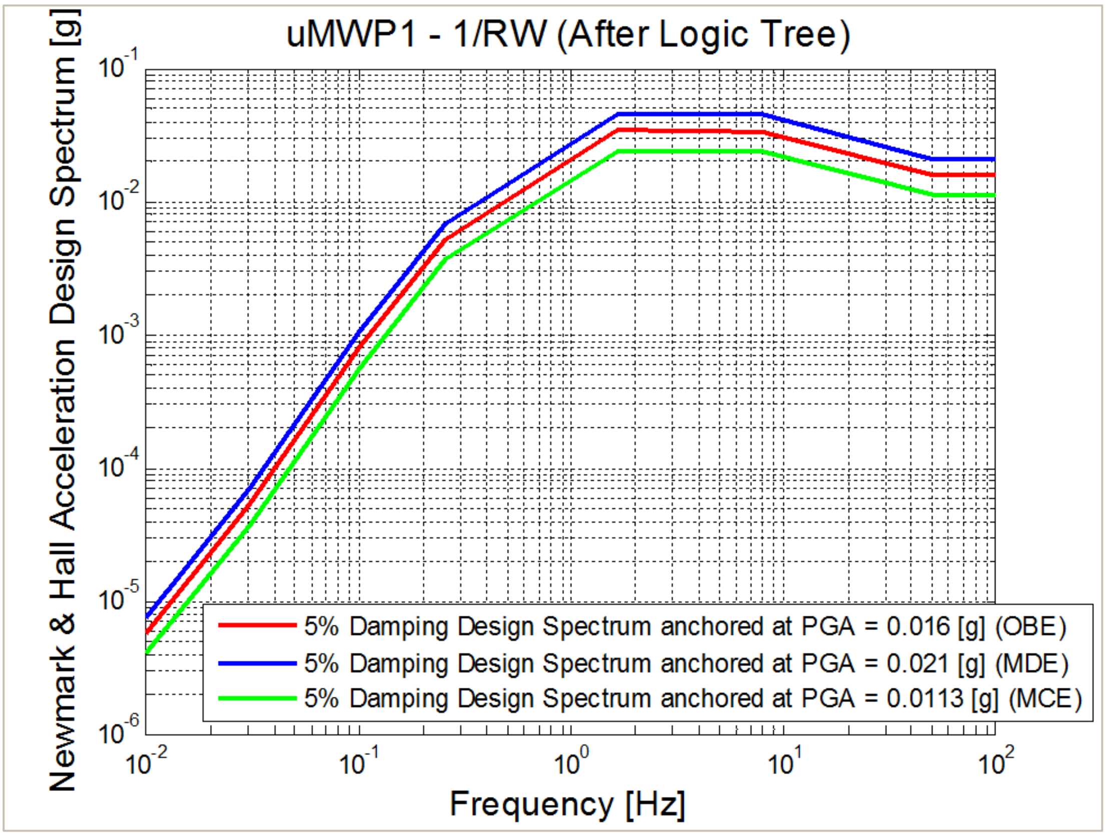

Figure 5.7: Newmark-Hall elastic design spectra anchored at the OBE, MDE and MCE values of horizontal PGA, resulting from application of logic tree procedure.

5.3 UNIFORM HAZARD SPECTRA (UHS)

The Uniform Hazard Spectrum (UHS) represents a constant probability or uniform hazard (response) spectrum. Essentially, it shows ground motion amplitudes over a number of oscillator periods of engineering interest at the same return period or probability of exceedance.

The Uniform Hazard Spectrum, (UHS), known also as a uniform acceleration response spectrum is actually a lateral slice of an ensemble of hazard curves for a given probability of exceedance (or equivalent return period), where each curve represents the acceleration at a particular frequency.

The UHS does not reflect the shape of the spectrum of any particular earthquake, but provides a combination of contributions from distant large magnitude events and nearer, smaller ones. This is a drawback if the spectrum is to be used directly for multi-mode analysis or to generate a strong motion record. However, for normal buildings, in low seismicity areas, the main need is to provide a single, frequency dependent indicator of lateral strength requirement, for which refinement of considering multi-modes is not necessary. Moreover, the UHS can be used as an envelope criterion for the spectra from a set of real time histories which can be used in more advanced designs.

Figure 5.8 and **Figure 5.9** shows horizontal UHS for the Smithfield Dam site calculated for GMPE AB06 (*Atkinson and Boore, 2006*) and BA08 (*Boore and Atkinson, 2008*). The UHSs are calculated as a function of ground motion vibration frequency for 3 probabilities of annual exceedance: 0.50%, 0.10% and 0.01%. The same spectra calculated for 7 return periods: 100; 200; 475; 1 000; 10 000; 100 000 and a million years expressed in terms of both ground motion vibration frequency and ground motion vibration period are shown in **Appendix E**.

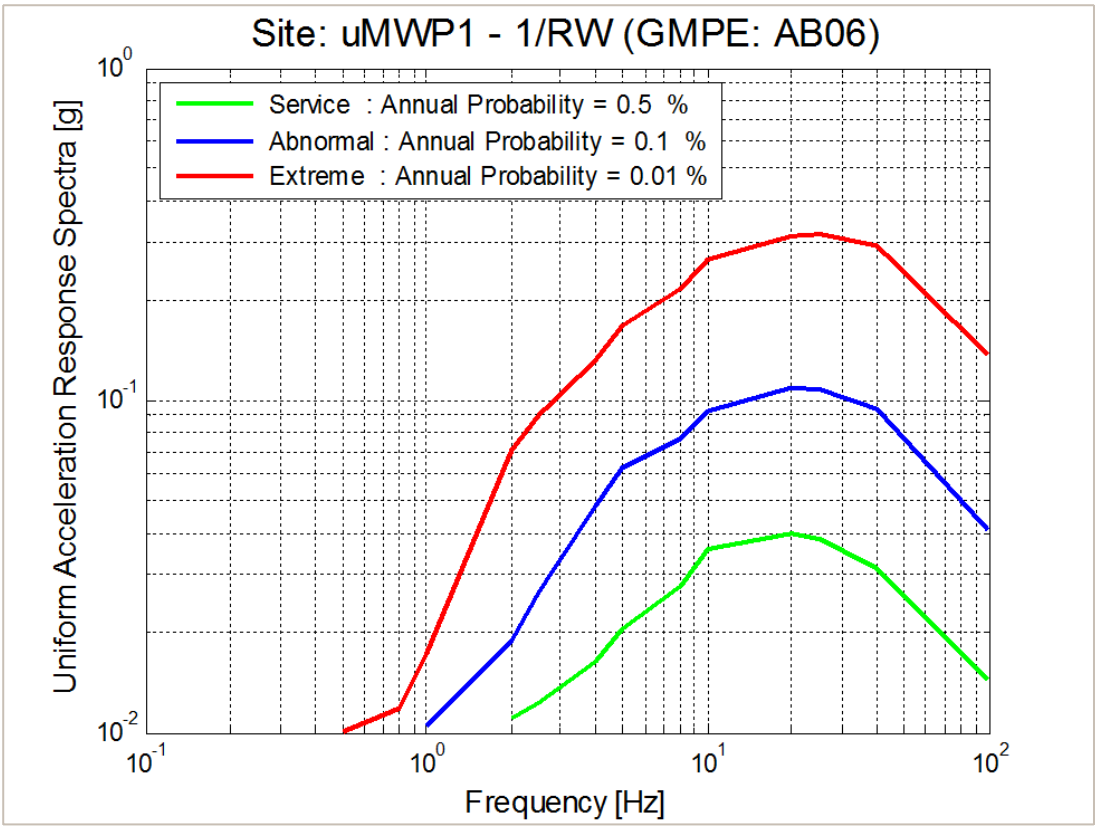

Figure 5.8: Horizontal Uniform Acceleration Response Spectra in terms of ground motion vibration frequency, calculated for ground motion prediction equation AB06 (Atkinson and Boore, 2006).

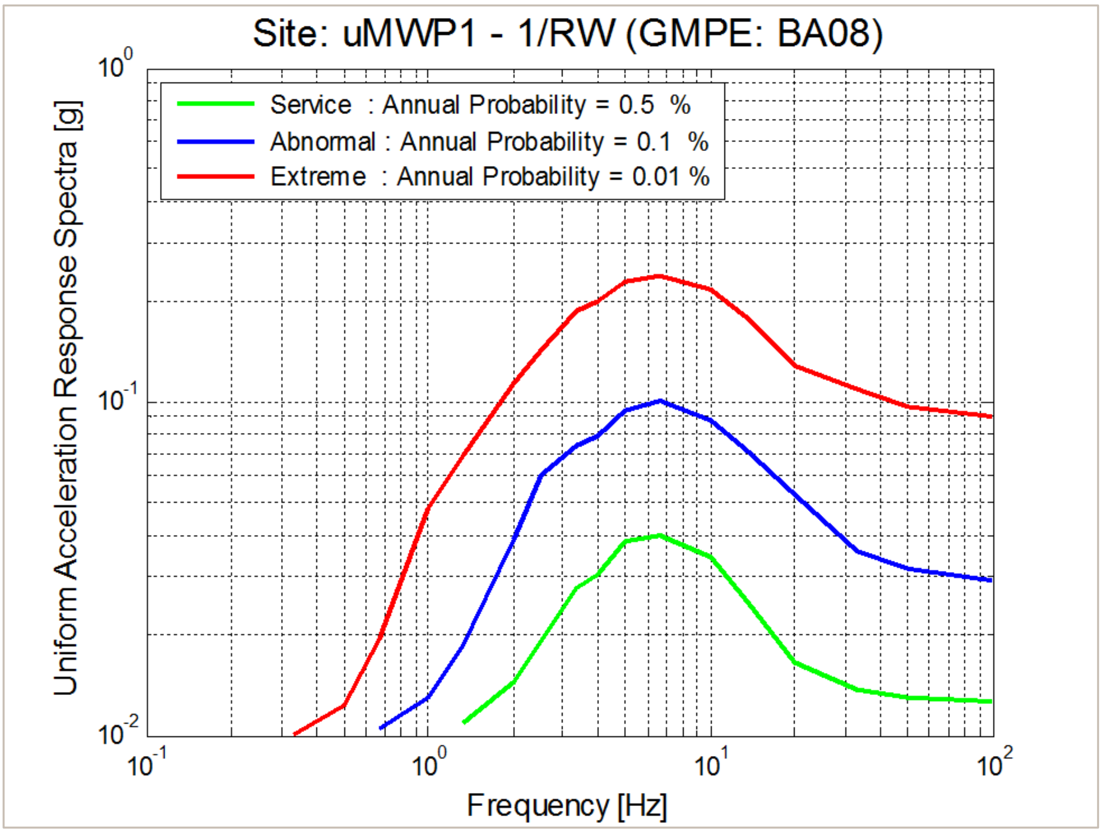

Figure 5.9: Horizontal Uniform Acceleration Response Spectra in terms of ground motion vibration frequency, calculated for ground motion prediction equation BA08 (Boore and Atkinson, 2008).

6 ACCOUNT OF UNCERTAINTIES: LOGIC TREE APPROACH

The purpose of this section is to provide an interpretation of uncertainties associated with the PSHA assessment performed for site of the Smithfield Dam.

The development of any complexity seismotectonic model needed by PSHA requires several essential assumptions about its parameters, parameters which are uncertain and allow a wide range of interpretations.

There are two types of uncertainty (variability) that can be included in PSHA. These are aleatory and epistemic (e.g. *Budnitz et al., 1997; Bernreuter et al., 1989*).

Aleatory variability is uncertainty in the data used in an analysis which accounts for randomness associated with the prediction of a parameter from a specific model, assuming that the model is correct. For example, standard deviation of the mean value of ground motion represents typical aleatory variability. Aleatory variability is included, by default, in the PSHA calculations by means of mathematical integration, which are an integral part of the applied methodology.

Epistemic variability accounts for incomplete knowledge in the predictive models and the variability in the interpretations of the data. Epistemic uncertainty is included in the PSHA by account of alternative hypothesis and models. For example, the alternative hypothesis accounts for uncertainty in earthquake source zonation, their seismic potential, seismic source hazard parameters and GMPE’s.

The lack of the reliable regional ground motion prediction equation and lack of knowledge of seismic potential of tectonic faults in vicinity of the dam site are the main sources of uncertainty in this PSHA assessment for the site of a Smithfield Dam. For this reason the effect of two alternative assumptions regarding GMPEs is investigated in detail.

Let us apply formalism of the logic tree to the 3 levels of required ground motions at the dam site (OBE, MDE and MCE).

Let us assume that that the probability of being correct for each of the two applied GMPEs are the same and equal to 0.50. Based on the logic tree formalism and **Table 5.1**, the expected values of horizontal component of OBE, MDE and MCE for the site of the Smithfield Dam are:

- OBE (Return Period 144 years) = 0.50 * 0.016g + 0.50 * 0.015g ≅ 0.016g
- MDE (Return Period 475 years) = 0.50 * 0.024g + 0.50 * 0.018g ≅ 0.021g
- MCE (Return Period 10,000 years) = 0.50 * 0.137g + 0.50 * 0.090g ≅ 0.113g.

According to the applied guidelines, the site of the future dam is rated as low risk.

All quantitative assessments of seismic hazard done for site of the Smithfield Dam are applicable to all engineering structures which are located in a radius of up to ca. 50km from the site of the dam. The above statement must be verified, if in the vicinity of the structures there are tectonic active faults present, i.e. faults which are capable of generating seismic events.

7 CONCLUSIONS

The PSHA was performed using the conventional, Cornell-McGuire procedure (*Cornell, 1968; McGuire, 1976, 1978*). The earthquake recurrence parameters *b*-value, λ, and m_{max} were calculated by the procedure of *Kijko and Sellevoll (1989, 1992)* and *Kijko (2004)*.

In general, a PSHA procedure requires knowledge of regional geology, tectonics, paleo- historic and instrumentally recorded seismicity. Unfortunately, at this stage of the investigation, not all of the required information was available. The incompleteness of information (in our case information about the seismotectonic model of the area) contributes to the uncertainties of the PSHA assessment.

All calculations are repeated two times, each for a different ground motion prediction equation.

The uncertainties in the GMPE have been taken into account through logic tree formalism. The logic tree allows inclusions of alternative scenarios and interpretations that are weighted according to their probability of being correct.

Following the international guidance, (*ICOLD, 1989; Engineering and Design, ER 1110, 1995*), three designed levels of PGA were considered, Operating Basis Earthquake, OBE, (return period 144 years); Maximum Design Earthquake, MDE, (return period 475 years) and Maximum Credible Earthquake, MCE (return period 10,000 years).

The uniform acceleration response spectra and the 5% damping Newmark-Hall elastic design spectra are also provided.

According to the applied guidelines, the site of the future dam is rated as low risk.

The lack of a reliable regional ground motion prediction equation, tectonics, paleo, historic and instrumentally recorded seismicity, information about seismogenic zones and seismic capability of tectonic faults in the vicinity of the dam site are the major sources of uncertainty in this PSHA assessment. The site and surrounding areas are furthermore covered by widespread recent deposits, which made it difficult to extrapolate known existing structural features in the vicinity of the site. The uncertainty can be significantly reduced by the implementation of the results of a site specific structural geological study of the area, including neotectonic and palaeo-seismic aspects.

Substantial uncertainties exist regarding the seismic potential (seismic capability) of tectonic faults in radius of 320 km from the site.

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Appendix A

Seismicity of area surrounding the Smithfield Dam, KwaZulu-Natal, South Africa

year	month	day	lat	long	magnitude
1854	8	20	-29.70	31.00	3.70
1860	6	15	-29.90	31.00	3.70
1860	9	21	-29.60	30.40	3.70
1862	6	16	-29.90	31.00	3.70
1870	8	3	-28.30	29.10	5.00
1871	4	15	-32.10	28.30	3.70
1883	9	26	-29.80	27.40	3.00
1898	8	11	-29.70	31.10	3.00
1905	11	15	-27.50	31.50	3.70
1905	11	28	-30.50	29.40	3.70
1905	12	1	-30.50	29.40	3.70
1907	3	20	-29.90	30.30	3.00
1908	6	13	-27.70	30.70	3.00
1909	4	15	-30.70	30.00	3.70
1913	9	17	-30.50	29.40	3.70
1914	2	6	-29.00	31.70	3.00
1914	2	16	-29.00	31.70	4.30
1914	3	31	-28.70	31.90	3.70
1914	6	14	-29.30	31.30	3.00
1915	7	10	-27.90	31.40	4.00
1916	3	24	-28.90	31.70	3.00
1916	7	21	-27.70	29.90	3.70
1917	4	11	-28.90	31.70	3.70
1917	4	25	-28.00	31.00	3.70
1917	9	9	-28.00	31.00	3.70
1917	9	20	-28.00	31.00	3.00
1919	5	14	-28.00	31.00	3.00
1919	5	15	-28.00	31.00	3.70
1919	6	24	-30.50	29.40	3.00
1919	11	7	-28.00	31.00	3.70
1920	1	31	-29.30	31.30	3.00
1920	3	7	-28.00	31.00	3.00
1920	4	3	-28.00	31.00	3.70
1920	4	12	-28.00	31.00	3.00
1920	5	8	-30.50	29.40	3.00
1920	9	10	-30.50	29.40	3.70
1920	10	15	-30.50	29.40	3.00
1921	1	22	-30.50	29.40	4.30
1921	3	31	-27.00	30.80	3.00
1921	8	13	-30.50	29.40	4.30
1922	3	20	-30.50	29.40	4.30
1922	3	21	-28.00	31.00	3.70
1922	5	8	-28.00	31.00	3.00
1922	9	18	-30.50	29.40	3.70
1923	3	29	-28.00	31.00	4.00
1923	8	7	-30.50	29.40	3.00
1924	3	6	-30.50	29.40	3.70
1924	10	28	-30.50	29.40	3.00
1924	12	4	-27.50	28.70	3.70
1925	9	3	-30.50	29.40	3.70
1926	3	27	-27.80	30.80	3.70
1927	3	10	-28.40	32.30	3.70
1927	3	18	-27.00	30.80	3.00
1928	7	10	-30.40	27.70	3.00
1928	11	15	-28.90	31.50	3.70
1929	6	24	-28.90	31.70	3.70
1929	12	28	-30.50	29.40	3.70
1930	1	9	-27.30	30.10	4.00
1930	4	24	-30.50	29.40	3.70
1930	5	14	-28.90	31.70	3.00
1930	7	20	-30.20	30.00	4.30

1932	5	25	-29.30	30.00	3.00
1932	6	30	-30.50	29.40	3.70
1932	12	31	-28.30	32.50	6.30
1935	2	20	-28.70	31.90	3.00
1936	9	18	-28.40	32.30	3.00
1937	2	25	-30.40	29.00	3.00
1938	1	21	-30.50	29.40	3.70
1938	2	10	-27.80	31.30	4.30
1938	9	4	-32.40	28.70	3.00
1938	10	25	-28.20	28.70	3.70
1940	2	29	-28.60	28.20	4.30
1940	8	28	-30.00	30.50	3.00
1940	9	19	-28.60	31.40	3.00
1940	9	29	-30.80	30.20	3.70
1940	10	24	-30.00	30.50	3.00
1941	1	10	-27.40	31.60	3.70
1941	1	13	-27.40	31.60	3.70
1942	11	1	-31.10	30.50	5.50
1942	12	15	-31.10	30.20	3.00
1944	9	17	-27.60	30.80	4.30
1944	11	12	-29.00	27.70	4.30
1947	5	8	-28.60	32.10	3.70
1947	6	16	-27.20	28.50	3.70
1948	2	3	-29.10	30.60	4.30
1948	9	25	-30.30	29.90	4.30
1950	2	5	-31.20	29.80	3.70
1952	3	25	-30.00	28.30	3.50
1952	6	11	-30.10	29.80	4.20
1952	8	30	-30.00	27.50	3.40
1952	9	7	-29.00	28.00	3.80
1952	9	23	-30.00	29.00	3.20
1952	10	14	-29.80	27.00	4.40
1953	1	3	-30.50	27.50	3.40
1953	1	3	-30.50	27.50	3.40
1953	1	6	-30.50	27.50	3.60
1953	1	6	-30.50	27.50	3.40
1953	1	15	-30.50	27.50	4.70
1953	1	15	-30.50	27.50	3.30
1953	1	15	-30.50	27.50	3.40
1953	1	15	-30.50	27.50	3.50
1953	1	15	-30.50	27.50	4.00
1953	1	16	-30.50	27.50	3.80
1953	1	16	-30.50	27.50	3.20
1953	1	16	-30.50	27.50	3.60
1953	1	21	-30.50	27.50	3.90
1953	1	24	-30.50	27.50	3.60
1953	1	24	-30.50	27.50	4.20
1953	1	24	-30.50	27.50	3.50
1953	1	28	-30.50	27.50	3.40
1953	1	30	-30.50	27.50	4.40
1953	2	5	-30.50	27.00	3.40
1953	3	25	-30.30	28.50	3.50
1953	6	17	-30.00	28.50	3.90
1953	7	29	-30.50	28.00	3.60
1953	8	15	-30.50	28.50	3.00
1954	11	18	-28.20	27.20	4.30
1956	6	29	-28.30	31.30	3.00
1956	7	13	-30.30	29.70	4.20
1957	4	13	-30.50	27.20	5.50
1957	4	23	-30.30	27.20	4.70
1958	2	10	-29.30	28.20	3.80
1958	2	11	-29.30	28.20	3.80
1966	2	22	-29.00	28.00	3.80

1966	6	18	-29.30	29.30	5.00
1966	6	20	-28.30	31.00	4.00
1966	7	31	-32.50	29.80	4.10
1967	4	13	-29.70	29.00	4.20
1967	6	16	-30.20	27.60	3.60
1967	8	23	-29.70	30.00	3.80
1968	1	9	-29.80	28.30	3.30
1968	1	11	-30.30	28.50	3.90
1968	2	13	-29.40	27.10	3.10
1968	3	19	-29.90	28.30	3.20
1969	1	29	-30.40	27.60	3.20
1969	6	5	-29.90	30.30	3.40
1970	1	20	-29.90	29.90	3.20
1970	3	21	-28.30	27.70	3.30
1970	4	22	-27.90	31.70	3.70
1971	1	27	-27.50	31.10	4.99
1971	2	5	-29.60	28.10	5.41
1972	2	13	-29.30	27.20	3.60
1972	12	29	-28.20	27.20	4.20
1973	4	22	-30.60	27.40	3.50
1973	9	29	-28.20	27.20	3.20
1974	9	4	-29.80	29.50	3.80
1975	1	8	-29.60	30.40	3.50
1975	8	10	-30.30	27.70	4.10
1976	5	3	-29.70	28.10	3.60
1977	11	22	-28.18	28.84	3.10
1978	7	27	-29.40	31.40	3.30
1978	12	27	-28.40	28.60	4.00
1980	2	17	-27.20	30.90	5.41
1980	7	19	-28.10	27.80	3.00
1980	8	25	-28.70	32.70	5.15
1980	12	18	-29.30	29.10	5.09
1981	4	7	-30.90	30.20	3.40
1981	11	5	-29.90	27.30	4.00
1981	11	18	-28.20	31.80	4.10
1982	3	26	-27.30	29.00	4.30
1982	5	9	-29.60	27.00	3.30
1982	11	18	-29.40	27.50	3.60
1983	2	21	-27.97	31.39	3.01
1983	2	22	-29.16	27.79	4.38
1983	6	21	-32.38	29.58	3.83
1983	12	30	-29.82	27.27	3.89
1985	8	31	-30.10	27.13	3.06
1985	12	11	-29.77	28.02	3.56
1986	7	29	-29.63	27.50	3.22
1986	7	30	-30.87	28.29	3.00
1986	8	5	-28.20	28.10	3.00
1986	10	5	-30.24	28.15	5.15
1986	10	6	-30.03	28.61	3.17
1986	10	13	-30.26	27.69	3.62
1986	12	29	-29.98	27.61	3.09
1987	5	31	-30.40	30.40	5.04
1987	5	31	-30.40	30.40	4.83
1987	6	8	-30.01	27.13	3.36
1987	8	1	-30.35	28.34	4.22
1987	8	1	-30.60	28.13	3.73
1987	10	24	-30.63	29.01	4.33
1988	2	12	-30.28	28.57	4.30
1988	2	12	-30.15	28.37	4.05
1988	8	20	-29.42	30.10	3.67
1988	9	16	-29.52	27.57	3.26
1988	9	21	-31.03	28.70	3.04
1988	9	22	-30.61	28.89	3.16

1989	2	28	-30.82	28.23	3.43
1989	3	14	-30.07	28.67	3.04
1989	3	15	-30.03	29.04	3.06
1989	4	30	-30.56	29.01	3.37
1989	5	15	-31.51	28.49	3.51
1989	6	17	-29.74	27.14	3.89
1989	6	19	-29.89	27.18	3.18
1989	8	21	-29.48	30.83	3.91
1989	9	4	-29.10	27.58	3.37
1989	9	29	-30.64	28.43	5.00
1989	9	29	-30.79	28.99	3.18
1989	10	2	-29.98	28.05	3.76
1990	3	22	-28.06	30.56	3.70
1990	5	1	-29.82	27.70	3.90
1990	8	21	-30.25	28.87	3.10
1991	6	29	-30.69	28.51	3.70
1991	7	26	-30.01	29.19	3.60
1992	7	2	-27.59	30.70	3.50
1992	12	14	-27.08	30.25	3.44
1993	7	31	-29.60	27.71	3.80
1993	10	11	-28.48	30.67	3.30
1994	1	9	-29.50	30.20	3.70
1994	1	27	-30.82	28.86	3.60
1994	4	8	-30.60	30.89	3.40
1994	4	18	-28.15	28.90	3.10
1994	6	10	-30.06	29.61	3.20
1994	9	13	-30.39	29.12	3.20
1995	2	8	-29.73	27.55	3.70
1995	2	11	-30.46	30.27	3.30
1995	6	4	-27.73	30.12	3.00
1995	7	15	-27.65	29.75	3.30
1996	1	3	-29.23	28.50	3.00
1996	5	24	-30.08	27.37	3.10
1996	6	30	-28.18	29.84	3.20
1996	10	10	-29.20	30.63	3.40
1996	10	22	-30.50	29.06	3.50
1996	12	27	-31.01	30.30	3.80
1997	7	25	-29.38	27.79	3.20
1997	10	19	-28.36	31.83	3.50
1998	1	27	-27.78	32.02	3.70
1998	7	12	-30.68	27.31	3.90
1998	12	1	-27.70	30.16	3.50
1999	2	14	-30.22	29.37	4.10
2000	6	11	-31.36	29.85	4.10
2000	6	25	-29.33	27.31	3.20
2000	7	21	-29.69	27.27	3.10
2000	9	11	-27.33	29.32	3.20
2000	10	3	-30.26	28.24	3.20
2000	11	24	-28.54	28.50	3.30
2001	8	20	-30.40	29.58	3.10
2002	1	27	-29.81	27.64	4.90
2002	1	27	-29.58	27.49	4.70
2002	6	25	-29.91	27.04	3.50
2002	6	28	-28.14	31.35	3.70
2003	7	2	-29.81	27.13	3.00
2003	7	4	-30.00	27.10	3.30
2003	7	4	-30.00	27.04	3.00
2003	7	15	-28.52	28.58	3.40
2003	8	16	-27.09	29.57	3.30
2003	8	20	-27.42	28.98	3.30
2003	8	20	-26.91	29.96	3.00
2003	8	23	-26.92	30.09	3.30
2003	8	25	-26.98	29.25	3.60

2003	8	28	-27.29	30.16	3.10
2003	8	29	-26.99	30.07	3.20
2003	8	30	-28.28	28.27	3.50
2003	9	1	-27.14	29.55	3.10
2003	9	1	-26.95	30.43	3.50
2003	9	3	-28.04	28.48	3.50
2003	10	3	-29.77	27.45	3.60
2003	11	1	-30.40	28.15	3.00
2003	11	12	-30.56	27.70	3.00
2003	12	10	-30.32	27.67	3.70
2004	3	2	-27.12	29.47	3.30
2004	5	7	-32.08	30.36	3.70
2004	6	10	-30.11	28.10	3.40
2004	6	11	-30.19	27.94	3.00
2004	6	19	-29.99	27.19	3.20
2004	10	30	-31.90	29.48	3.40
2005	1	7	-29.96	27.30	4.20
2005	1	16	-28.00	29.54	3.50
2005	4	16	-29.75	27.33	3.20
2005	5	18	-29.73	27.85	3.30
2005	5	18	-29.45	28.23	3.60
2005	6	23	-30.25	29.73	3.20
2005	9	4	-27.27	30.97	3.60
2006	2	26	-29.95	26.64	3.10
2006	5	29	-28.04	31.27	3.70
2006	6	24	-29.16	33.16	4.80
2006	11	17	-29.43	32.96	3.90
2006	12	10	-31.79	28.79	3.30
2007	1	21	-30.22	28.16	3.10
2007	3	2	-29.57	28.44	3.30
2007	3	6	-30.23	28.17	3.20
2007	4	9	-29.82	26.79	4.00
2007	6	3	-30.19	28.57	3.70
2007	12	26	-29.96	29.50	3.70
2008	2	28	-28.73	30.90	3.60
2008	12	20	-28.74	32.82	3.60
2009	1	8	-28.72	32.66	4.10
2009	1	27	-30.22	29.28	3.70
2009	3	7	-28.33	32.35	4.70
2009	4	28	-31.84	30.07	5.50
2009	5	20	-29.65	27.68	3.60
2009	5	21	-28.64	28.98	3.50
2009	5	21	-28.63	28.99	3.70
2009	7	5	-30.93	29.29	3.10
2010	2	16	-28.86	26.84	3.10
2010	3	3	-30.49	31.00	3.40
2010	3	13	-27.02	29.54	3.80
2010	3	14	-28.14	29.11	4.00
2010	3	19	-27.54	31.46	3.40
2010	3	21	-28.08	27.90	4.00
2010	6	29	-31.04	30.20	5.60
2010	6	30	-28.93	32.05	4.70
2010	7	9	-30.76	27.82	4.80
2010	7	12	-28.15	28.88	4.30
2010	10	16	-28.51	29.68	3.90
2010	10	18	-30.09	27.30	4.30

Appendix B

Applied Methodology for Probabilistic Seismic Hazard Analysis

1. Introduction

The essence of the Probabilistic Seismic Hazard Analysis (PSHA) is the calculation of the probability of exceedance of a specified ground motion level at a specified site (Cornell, 1968; Reiter, 1990). In principle, PSHA can address a very broad range of natural hazards associated with earthquakes, including ground shaking and ground rupture, landslide, liquefaction or tsunami. However, in most cases, the interest of designers is in the estimation of likelihood of a specified level of ground shaking, since it causes the greatest economic losses.

The typical output of the PSHA is **seismic hazard curve** (often, a set of seismic curves), i.e. plots of the estimated probability, per unit time, of the ground motion variable, e.g. peak ground acceleration (PGA) being equal to or exceeding the level as a function of PGA (Budnitz *et al*., 1997). The essence of the PSHA is that its product – the seismic hazard curve, quantifies the hazard at the site from all possible earthquakes of all possible magnitudes at all significant distances from the site of interest, by taking into account their frequency of occurrences. In addition to hazard curve, the output of PSHA includes results of the so called deaggregation procedure. The procedure provides information on earthquake magnitudes and distances that contribute to the hazard at a specified return period, and at a structural period of engineering interest (Budnitz *et al*., 1997).

In general, the standard PSHA procedure is based on two sources of information: (1) observed seismicity, recapitulated by seismic event catalogue, and (2) area-specific, geological data. After the combination of a selected model of earthquake occurrence with the information on the regional seismic wave attenuation or ground motion prediction equation (GMPE), a regional seismotectonic model of the area is formulated. In addition, the PSHA takes into account the site specific soil properties.

Complete PSHA can be performed only when information on the regional seismotectonic model and the site-specific soil properties are known.

Clearly, all above information, required by a complete PSHA is subjective and often, highly uncertain especially in stable continental areas where the earthquake activity is very low. According to convention established in the fundamental document by Budnitz *et al*. (1997), there are two types of uncertainties, associated with PSHA: these are **aleatory** and **epistemic** uncertainties. According to Budnitz *et al*. (1997), the uncertainties that are part of the applied model used in the analysis, are called aleatory uncertainties. The other names for the aleatory uncertainty are ‘stochastic’ or ‘random’ uncertainties. Even when the model is perfectly correct, and the numerical values of its parameters are known without any errors, aleatory uncertainties (for a given model) are still present (Budnitz *et al*. 1997).

The uncertainties which come from incomplete knowledge of the models, i.e. when wrong models are applied or/and the numerical values of their parameters are not known, are called epistemic uncertainties. As relevant information is collected, the epistemic uncertainties can be reduced (Budnitz *et al.*, 1997).

By definition of the PSHA procedure, the aleatory uncertainty is included in the process of PSHA calculations by means of applied models (statistical distributions) and by mathematical integration. Epistemic uncertainty can be incorporated in the PSHA by consideration of an alternative hypothesis (e.g. alternative boundaries of the seismic sources and their recurrence parameters), and alternative models (e.g. alternative earthquake distributions or/and application of alternative PGA attenuation equations). Incorporation of this type of uncertainties into the PSHA is performed by application of the logic tree formalism.

A complete PSHA includes an account of aleatory as well as epistemic uncertainties. Any PSHA without the incorporation of the above uncertainties is considered to be incomplete.

This Appendix concentrates on two major mathematical aspects of the PSHA:

(1) The procedure for assessment of the seismic source characteristic, recurrence parameters when the data are incomplete and uncertain. Use is made of the most common assumptions in engineering seismology i.e. those earthquake occurrences in time follow a Poisson process and that earthquake magnitudes are distributed according to a Gutenberg-Richter doubly-truncated distribution. Following the above assumptions, seismic source recurrence parameters: the mean seismic activity rate, λ (which is a parameter of the Poisson distribution); the level of completeness of the earthquake catalogue m_{min}, the maximum regional earthquake magnitude m_{max}, and the Gutenberg-Richter parameter b. To assess the above parameters, a seismic event catalogue containing origin times, size of seismic events and spatial locations is needed. The maximum seismic source characteristic earthquake magnitude m_{max} is of

paramount importance in this approach; therefore a statistical technique that can be used for evaluating this important parameter is presented.

(2) PSHA methodology i.e. calculating the probability of exceedance of a specified ground motion level at a specified site. Often, the presented approach is known as the Cornell-McGuire procedure.

2. Estimation of the Seismic Source Recurrence Parameters – Bayesian Approach

This section gives an outline of the procedure used to determine the seismic source recurrence parameters: the mean seismic activity rate λ, the Gutenberg-Richter parameter b, and the maximum regional earthquake magnitude m_{max}.

2.1 Nature of input data

The lack, or incompleteness, of data in earthquake catalogues is a frequent issue in a statistical analysis of seismic hazard. Contributing factors include the historical and socio–economic context, demographic variations and alterations in the seismic network. Generally, the degree of completeness is a monotonically increasing function of time, i.e. the more recent portion of the catalogue has a lower level of completeness. The methodology makes provision for the earthquake catalogue to contain three types of data: (1) very strong prehistoric seismic events (paleo-earthquakes), which usually occurred over the last thousands of years; (2) the macro-seismic observations of some of the strongest seismic events that occurred over a period of the last few hundred years; and (3) complete recent data for a relatively short period of time. The complete part of the catalogue can be divided into several sub-catalogues, each of which is complete for events above a given threshold magnitude $m_{min}^{(i)}$, and occurring in a certain period of time T_i where $i = 1, \ldots, s$ and s is the number of complete sub-catalogues. The approach permits 'gaps' (T_g) when records were missing or the seismic networks were out of operation. Uncertainty in earthquake magnitude is also taken into account in that an assumption is made that the observed magnitude is true magnitude subjected to a random error that follows a Gaussian distribution having zero mean and a known standard deviation. Figure 2.1 depicts the typical scenario confronted when conducting seismic hazard assessments.

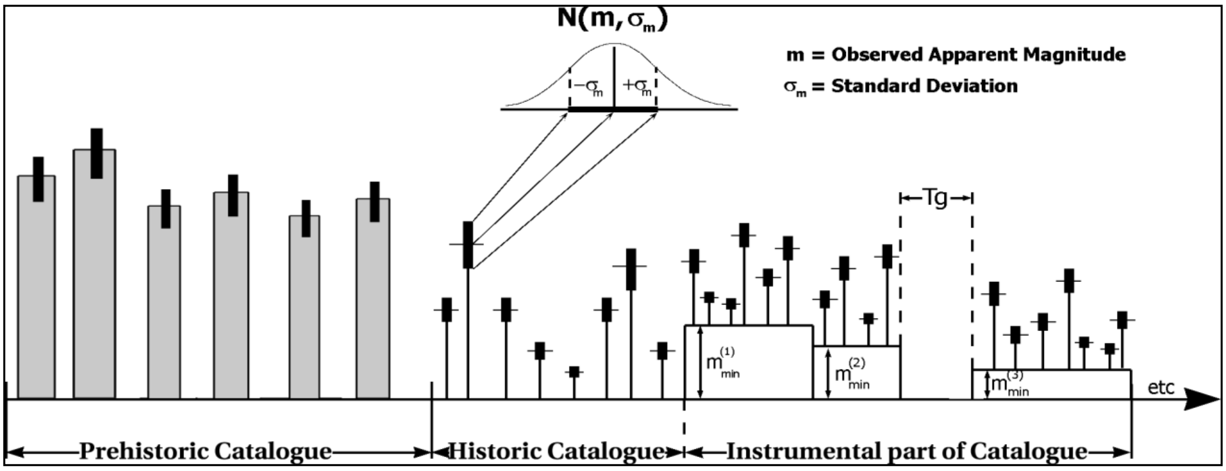

Figure 1 Illustration of data which can be used to obtain reccurence parameters for the specified seismic source. The approach permits the combination of the largest earthquakes (prehistoric/paleo- and historic) data and complete (instrumental) data having variable threshold magnitudes. It accepts 'gaps' (T_g) when records were missing or the seismic networks were out of operation. The procedure is capable of accounting for uncertainties of occurrence time of prehistoric earthquakes. Uncertainty in earthquake magnitude is also taken into account, in that an assumption is made that the observed magnitude, is true magnitude subjected to a random error that follows a Gaussian distribution having zero mean and a known standard deviation. (Modified after Kijko and Sellevoll, 1992)

2.1.1 Statistical preliminaries

Basic statistical distributions and quantities utilized in the development of the methodology are briefly described in what follows.

The Poisson distribution is used to model the number of occurrences of a given earthquake magnitude or a given amplitude of a selected ground motion parameter being exceeded within a specified time interval.

$$p(n|\lambda,t) = P(N = n|\lambda,t) = \frac{(\lambda t)^n}{n!} e^{-\lambda t} \quad n = 0,1,2,... \tag{1}$$

Note that λ here refers to the mean of the distribution, and describes the mean activity rate (mean number of occurrences).

The gamma distribution, given its flexibility, is used to model the distribution of various parameters in our approach, and is given by

$$f(x) = (x)^{q-1} \frac{p^q}{\Gamma(q)} e^{-p\,x}, \qquad x > 0 \;, \tag{2}$$

where $\Gamma(q)$ is the gamma function defined as

$$\Gamma(q) = \int_0^\infty y^{q-1} e^{-y} dy, \quad q > 0\,, \tag{3}$$

The parameters p and q are related to the mean μ, and variance σ^2, of the distribution according to

$$\mu_x = \frac{q}{p}\;, \tag{4}$$

$$\sigma_x{}^2 = \frac{q}{p^2}\,, \tag{5}$$

The coefficient of variation expresses the uncertainty related to a given parameter, and is given by

$$COV_x = \frac{\sigma_x}{\mu_x}\,, \tag{6}$$

thus describing the variation of a parameter relative to its mean value, with a higher value indicating a greater dispersion of the parameter.

2.2.2 Estimation of the seismic source recurrence parameters

The standard assumption adopted is that the distribution of earthquakes, with respect to their size, obeys the classic Gutenberg-Richter relation

$$\log N(m) = a - b \cdot (m - m_{\min}) \;, \tag{7}$$

where $N(m)$ is the number of earthquakes of $m \geq m_{\min}$, occurring within a specified period of time, and a and b are parameters.

Aki (1965) found that equation (7) implied a singly truncated exponential distribution of the form

$$\begin{aligned} F_M(m) &= P(M \le m) \\ &= 1 - e^{-\beta(m - m_{\min})} \end{aligned}, \qquad (8)$$

where $\beta = b\ln(10)$.

The earthquake occurrences over time in the given area are assumed to satisfy a Poisson process (1) having an unknown mean seismic activity rate λ.

The disregard of temporal and spatial variations of the parameters λ and b can lead to biased estimates of seismic hazard. An explicit assumption behind most hazard assessment procedures is that parameters λ and b and remain constant in time. However, examination of most earthquake catalogues indicates that there are temporal changes of the mean seismic activity rate λ as well as of the parameter b. For some seismic areas, the b-value has been reported to change (decrease/increase) its value before large earthquakes. Usually, such changes are explained by the state of stress; the higher the stress, the lower the b-value. Other theories connect the b-value with the homogeneity of the rock: the more heterogeneous the rock, the higher the b-value. Finally, some scientists connect the fluctuation of the b-value with the seismicity pattern and believe that the b-value is controlled by the buckling of the stratum. Whatever the mechanism, the phenomenon of space-time b-value fluctuation is indubitable and well-known. A wide range of international opinions concerning changes of patterns in seismicity, together with an extensive reference list, are found in a monograph by Simpson and Richards (1981) and in two special issues of *Pure and Applied Geophysics*, (Seismicity Patterns …, 1999; Microscopic and Macroscopic …, 2000). Treating both parameters λ and b as random variables modelled by respective gamma distributions, allows for appropriately accounting for the statistical uncertainty in these important parameters. In practice, the adoption of the gamma distribution does not really introduce much limitation, since the gamma distribution can fit a large variety of shapes. Combining the Poisson distribution (1) together with the gamma distribution (2) with parameters p_λ and q_λ, the probability related to a certain number of earthquakes, n, per unit time t, for randomly varying seismicity is obtained

$$P(n|t) = \int_0^\infty p(n|\lambda_A, t) f(\lambda_A) d\lambda_A = \frac{\Gamma(n+q_\lambda)}{n!\Gamma(q_\lambda)} \left(\frac{p_\lambda}{t+p_\lambda}\right)^{q_\lambda} \left(\frac{t}{t+p_\lambda}\right)^n, \tag{9}$$

where $p_\lambda = \bar{\lambda}/\sigma_\lambda^2$, $q_\lambda = \bar{\lambda}^2/\sigma_\lambda^2$ and $\Gamma(\cdot)$ is the Gamma function (3). Parameter $\bar{\lambda}$ denotes the mean value of activity rate λ.

Similarly, combining the exponential distribution (8) with the gamma distribution for β with parameters p_β and q_β, and normalizing (e.g. Campbell, 1982) upon introducing an upper limit $m_{\max}$ for the distribution of earthquake magnitudes, the CDF of earthquake magnitudes is obtained

$$F_M(m|m_{\min}) = C_\beta \left[1 - \left(\frac{p_\beta}{p_\beta + m - m_{\min}}\right)^{q_\beta}\right], \tag{10}$$

where $p_\beta = \bar{\beta}/\sigma_\beta^2$ and $q_\beta = \bar{\beta}^2/\sigma_\beta^2$. The symbol $\bar{\beta}$ denotes the mean value of parameter β, σ_β denotes the standard deviation of β and the normalizing coefficient C_β is given by

$$C_\beta = \left[1 - \left(\frac{p_\beta}{p_\beta + m_{\max} - m_{\min}}\right)^{q_\beta}\right]^{-1}, \tag{11}$$

Noting that $q_\lambda = \bar{\lambda} \cdot p_\lambda$ and $q_\beta = \bar{\beta} \cdot p_\beta$, equations (9) and (10) may alternatively be written respectively as

$$P(n|t) = \frac{\Gamma(n+q_\lambda)}{n!\Gamma(q_\lambda)} \left(\frac{q_\lambda}{\bar{\lambda}_A t + q_\lambda}\right)^{q_\lambda} \left(\frac{\bar{\lambda}_A t}{\bar{\lambda}_A t + q_\lambda}\right)^n, \tag{12}$$

and

$$F_M(m|m_{\min}) = C_\beta \left[1 - \left(\frac{q_\beta}{q_\beta + \beta(m - m_{\min})} \right)^{q_\beta} \right], \tag{13}$$

with

$$C_\beta = \left[1 - \left(\frac{q_\beta}{q_\beta + \beta(m_{\max} - m_{\min})} \right)^{q_\beta} \right]^{-1}, \tag{14}$$

Note that $q_\beta = \left(COV_\beta^{-1}\right)^2$ and $q_\lambda = \left(COV_\lambda^{-1}\right)^2$. Upon specification of the COV, the parameters $\bar{\lambda}$ and $\bar{\beta}$, referred to as hyper-parameters of the respective distributions are estimated on the basis of observed data by applying the maximum likelihood procedure.

2.3.1 Extreme magnitude distribution as applied to prehistoric (paleo) and historic events

The likelihood function of desired seismicity parameters $\boldsymbol{\theta} = (\bar{\lambda}, \bar{\beta})$ is built based on the prehistoric (paleo) and historic parts of the catalogue containing the strongest events only. In this section the details of the likelihood function based on historic earthquakes will be discussed, since except for a few details, the likelihood function based on prehistoric events is built in a similar manner.

By the Theorem of the Total Probability (e.g. Cramér, 1961), the probability that in time interval t either no earthquake occurs, or all occurring earthquakes have magnitude not exceeding m, may be expressed as (Epstein and Lomnitz, 1966; Gan and Tung, 1983; Gibowicz and Kijko, 1994)

$$F_M^{\max}(m \mid m_0, t) = \sum_{i=0}^{\infty} P(i|t)\left[F_M(m \mid m_0)\right]^i, \tag{15}$$

Relation (15) can be expressed in a much more simpler form (e.g. Campbell, 1982), which may be written as

$$F_M^{\max}\left(m \mid m_0, t\right)=\left[\frac{q_\lambda}{q_\lambda+\bar{\lambda}_0 t\left[1-F_M\left(m \mid m_0\right)\right]}\right]^{q_\lambda}, \qquad (16)$$

In relations (15) and (16), m_0 is the threshold magnitude for the prehistoric or historic part of the catalogue ($m_0 \geq m_{\min}$). Magnitude $m_{\min}$ is the 'total' threshold magnitude and has a rather formal character. The only restriction on the choice of its value is that $m_{\min}$ may not exceed the threshold magnitude of any part - prehistoric, historic or complete - of the catalogue.

It follows from relation (16) that the probability density function (PDF) of the largest earthquake magnitudes m within a period t is

$$f_M^{\max}(m \mid m_0, t)=\frac{\bar{\lambda}_0 t q_\lambda f_M(m \mid m_0) F_M^{\max}(m \mid m_0, t)}{q_\lambda+\bar{\lambda}_0 t[1-F_M(m \mid m_0)]}, \qquad (17)$$

$\bar{\lambda}_0$ represents the mean of the distribution of the mean activity rate for earthquakes with magnitudes not less than m_0, and is given by

$$\bar{\lambda}_0=\bar{\lambda}_A\left[1-F_M\left(m \mid m_0\right)\right], \qquad (18)$$

where $\bar{\lambda}_A$, as defined above, is the mean of the distribution of the mean activity rate corresponding to magnitude value $m_{\min}$. Function $f_M\left(m \mid m_0\right)$ denotes the PDF of earthquake magnitude. Based on (13) and the definition of the probability density function, it takes the following form:

$$f_M(m)=C_\beta \bar{\beta}\left(\frac{q_\beta}{q_\beta+\bar{\beta}\left(m-m_0\right)}\right)^{q_\beta+1}, \qquad (19)$$

After introducing the PDF (17) of the largest earthquake magnitude m within a period t, the likelihood function of unknown parameters $\boldsymbol{\theta}$ becomes:

$$L_0\left(\boldsymbol{\theta} \mid \boldsymbol{m}_0, \boldsymbol{t}_0, \boldsymbol{cov}\right)=\prod_{i=1}^{n_0} f_M^{\max}\left(m_{0i} \mid m_0, t_i\right), \qquad (20)$$

In order to build the likelihood function (20), three kinds of input data are required: $\boldsymbol{m}_0$, t, and $\boldsymbol{cov}$, where $\boldsymbol{m}_0$ is vector of the largest magnitudes, t denotes vector of the time intervals within which the largest events occurred, and vector $\boldsymbol{cov} = (\text{cov}_\lambda, \text{cov}_\beta)$, consists of the coefficients of variation (amount of dispersion (uncertainty relative to the mean) of the unknown parameters $\boldsymbol{\theta} = (\bar{\lambda}, \bar{\beta})$.

2.3.2 *Combination of extreme and complete seismic catalogues with different levels of completeness*

If it is assumed that the third, complete part of the catalogue can be divided into s sub-catalogues (Kijko and Sellevoll, 1992), each of them has a span T_i and is complete starting from the known magnitude $m_{\min}^{(i)}$. For each sub-catalogue i, $\boldsymbol{m}_i$ is used to denote n_i earthquake magnitudes m_{ij}, where $m_{ij} \geq m_{\min}^{(i)}, i = 1,\ldots,s$ and $j = 1,\ldots,n_i$. Let $L_i(\boldsymbol{\theta}|\boldsymbol{m}_i)$ denote the likelihood function of the unknown $\boldsymbol{\theta} = (\bar{\lambda}, \bar{\beta})$, based on the i-the complete sub-catalogue. If the size of seismic events is independent of their number, the likelihood function $L_i(\boldsymbol{\theta}|\boldsymbol{m}_i)$ is the product of two functions, $L_i(\bar{\lambda}|\mathbf{m}_i)$ and $L_i(\bar{\beta}|\boldsymbol{m}_i)$.

The assumption that the number of earthquakes per unit time is distributed according to (12) means that $L_i(\bar{\lambda}|\mathbf{m}_i)$ has the following form:

$$L_i(\bar{\lambda}|\mathbf{m}_i) = const \cdot (\bar{\lambda}^{(i)} t + q_\lambda)^{-q_\lambda} \left(\frac{\bar{\lambda}^{(i)} t}{\bar{\lambda}^{(i)} t + q_\lambda} \right)^{n_i}, \qquad (21)$$

where $const$ does not depend on $\bar{\lambda}$ and $\bar{\lambda}^{(i)}$ is the mean activity rate corresponding to the threshold magnitude $m_{\min}^{(i)}$ and is given by,

$$\bar{\lambda}^i = \bar{\lambda} \left[1 - F_M(m_{\min}^{(i)} \mid m_{\min})\right], \qquad (22)$$

Following the definition of the likelihood function based on a set of independent observations, and (19), $L_i(\beta|\boldsymbol{m}_i)$ takes the form

$$L_i(\overline{\beta}|\boldsymbol{m}_i)=\left[C_\beta\ \overline{\beta}\right]^{n_i}\prod_{j=1}^{n_i}\left[1+\frac{\overline{\beta}}{q_\beta}\left(m_{ij}-m_{\min}^{(i)}\right)\right]^{-(q_\beta+1)}, \qquad (23)$$

Relations (21) and (23) define the likelihood function of the unknown parameters $\boldsymbol{\theta}$ = ($\overline{\lambda}_A, \overline{\beta}$) for each complete sub-catalogue.

Finally, $L(\boldsymbol{\theta})$, the joint likelihood function based on all data, i.e. the likelihood function based on the whole catalogue, is calculated as the product of the likelihood functions based on prehistoric, historic and complete data.

The maximum likelihood estimates of the required hazard parameters $\boldsymbol{\theta}$ = ($\overline{\lambda}, \overline{\beta}$), are given by the value of $\boldsymbol{\theta}$ which, for a given maximum regional magnitude $m_{\max}$, maximizes the likelihood function $L(\boldsymbol{\theta})$. The maximum of the likelihood function is obtained by solving the system of two equations $\frac{\partial \ell}{\partial \overline{\lambda}_A}=0$ and $\frac{\partial \ell}{\partial \overline{\beta}}=0$, where $\ell=\ln[L(\boldsymbol{\theta})]$.

A variance-covariance matrix $D(\boldsymbol{\theta})$, of the estimated hazard parameters, $\hat{\overline{\lambda}}$ and $\hat{\overline{\beta}}$, is calculated according to the formula (Edwards, 1972):

$$\mathrm{D}(\theta)=-\begin{bmatrix}\frac{\partial^2 \ell}{\partial \overline{\lambda}^2} & \frac{\partial^2 \ell}{\partial \overline{\lambda}\,\partial \overline{\beta}} \\ \frac{\partial^2 \ell}{\partial \overline{\beta}\partial \overline{\lambda}} & \frac{\partial^2 \ell}{\partial \overline{\beta}^2}\end{bmatrix}^{-1}, \qquad (24)$$

where derivatives are calculated at the point $\overline{\lambda} = \hat{\overline{\lambda}}$ and $\overline{\beta} = \hat{\overline{\beta}}$.

2.3 Estimation of the maximum regional earthquake magnitude $m_{\max}$

Suppose that in the area of concern, within a specified time interval T, there are n main seismic events with magnitudes $m_1, \ldots, m_n$. Each magnitude $m_i \geq m_{\min}$ ($i = 1, \ldots, n$), where $m_{\min}$ is a known threshold of completeness (i.e. all events having magnitude greater than or equal to $m_{\min}$ are recorded). It is further assumed that the seismic event magnitudes are independent, identically distributed, random variables with CDF described by equation (13).

From the condition that compares the largest observed magnitude $m_{\max}^{obs}$ and the maximum expected magnitude during a specified time interval T, the maximum regional magnitude $m_{\max}$ is obtained (Kijko and Graham, 1998; Kijko, 2004)

$$m_{\max} = m_{\max}^{obs} + \frac{\delta^{1/q} \exp\left[nr^q / \left(1 - r^q\right)\right]}{\bar{\beta}} \left[\Gamma\left(-1/q, \delta r^q\right) - \Gamma\left(-1/q, \delta\right)\right], \tag{25}$$

where $\delta = nC_\beta$ and $\Gamma(\cdot,\cdot)$ is the complementary incomplete gamma function. The approximate variance of the above estimator is equal to (Kijko, 2004)

$$\sigma_{m_{\max}}^2 \cong \sigma_M^2 + \left\{ \frac{\delta^{1/q} \exp\left[nr^q / \left(1 - r^q\right)\right]}{\bar{\beta}} \left[\Gamma\left(-1/q, \delta r^q\right) - \Gamma\left(-1/q, \delta\right)\right] \right\}^2, \tag{26}$$

where σ_M is the standard error in determination of the largest observed magnitude $m_{\max}^{obs}$.

3. The Cornell-McGuire PSHA Methodology

The essence of the PSHA is the calculation of the probability of exceedance of a specified ground motion level at a specified site. The so called, Cornell-McGuire solution of this problem consists of four steps: (e.g. Budnitz *et al*., 1997; Reiter, 1990):

1. Determination of the possible seismic sources around the site. The sources are typically identified faults, point sources, or area sources, in which it is assumed that the occurrence of earthquakes is spatially uniform. In the territory of Eastern and Southern Africa, like the central and eastern United States or Australia, the main

contribution to the seismic hazard comes from the area sources. The seismicity of the area not always correlates well with geological structures recognizable at the surface therefore identification of the geological structures that are responsible for earthquakes are difficult.

2. Determination and assessment of the recurrence parameters for each seismic source. This is typically expressed in terms of three parameters: the mean seismic activity rate λ, b-value of the Gutenberg – Richter frequency magnitude relation and the upper-bound of earthquake magnitude $m_{\max}$.

Selection of the ground motion prediction equation (GMPE), which is most suitable for the region, is crucial. For Eastern and Southern Africa areas, the strong motion records are very limited therefore theoretical models of the ground motion attenuation are used. Since the ground motion attenuation relationship is a major source of uncertainty in the computed PSHA, some codes and recommendations require use of a number of alternative GMPE's (Bernreuter *et al*., 1989).

3. Computation of the hazard curves. These curves are usually expressed in terms of the mean annual frequency of events with site ground motion level a or more, $\lambda(a)$ or probability of exceedance, Pr[A>a in time t], vs. a ground motion parameter a, like PGA or a spectral acceleration. By the Theorem of the Total Probability, (Cramér, 1961), the frequency $\lambda(a)$, is defined as (Budnitz, 1997)

$$\lambda(a) = \sum_{i=1}^{n_s} \lambda_i \int_{m_{\min}}^{m_{\max}} \int_{R|M} \Pr[A \geq a \mid M, R]\, f_M(m)\, f_{R|M}(r \mid m)\, dr\, dm \qquad (27)$$

in which the subscripts i, (i=1,...n_S), denoting seismic source number are deleted for simplicity. In equation (27), λ is the mean activity rate (per time unit and per seismic area unit) of earthquakes on seismic source i, having magnitudes between m_{min} and m_{max}; m_{min} is the minimum magnitude of engineering significance; m_{max} is the maximum earthquake magnitude assumed to occur on the seismic source; $\Pr[A \geq a|M,R]$ denotes the conditional probability that the chosen ground motion level is exceeded for a given magnitude and distance. Standard choice for $\Pr[A \geq a|M,R]$ is Gaussian complementary cumulative distribution function, which is based on the assumption that the ground motion parameter a is a lognormal random (aleatory) variable. In equation (27), $f_M(m)$ denotes the PDF of earthquake magnitude. In most engineering applications it is assumed that earthquake magnitudes follow the Gutenberg-Richter relation, which implies that $f_M(m)$ is negative, exponential distribution, with magnitudes between m_{min} and m_{max}. If uncertainty of the earthquake magnitude distribution is taken into account, $f_M(m)$ takes the familiar (Bayesian) form of equation (19). Finally, PDF $f_{R|M}(r|m)$ describes the spatial distribution of earthquake occurrence, or, more precisely, the PDF of distance from the earthquake source to the site of interest. In general cases, spatial distribution of the earthquake occurrence can be different for different earthquake magnitudes.

Under the condition that earthquake occurrence in every seismic source is Poisson event, i.e. independent in time and space, the ground motion $A \geq a$ at a site is also a Poisson event. Hence the probability, that *a*, a specified level of ground motion at a given site, will be exceeded at least once in any time interval *t* is

$$\Pr[A>a \text{ in time } t] = 1-\exp\left[-\sum_{i=1}^{n_s}\lambda_i \int_{m_{\min}}^{m_{\max}} \int_{R|M} \Pr[A \geq a \mid M,R]\, f_M(m)\, f_{R|M}(r \mid m)\, dr\, dm\right]. \qquad (28)$$

The equation (28) is fundamental in PSHA. The plot of this equation vs. ground motion parameter *a*, is the hazard curve – the ultimate product of the PSHA assessment.

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Appendix C

Seismic Sources and their Recurrence Parameters

Lat	Long	Depth	m_min	Lambda	b	m_max
-30.400	26.569	12.0	4.0	1.233237e-003	1.06	6.26
-30.150	26.569	12.0	4.0	1.298601e-003	1.05	6.24
-29.900	26.569	12.0	4.0	1.954856e-003	0.99	6.24
-29.650	26.569	12.0	4.0	2.665028e-003	0.96	6.24
-29.400	26.569	12.0	4.0	2.680913e-003	0.96	6.24
-29.150	26.569	12.0	4.0	2.716038e-003	0.96	6.24
-28.900	26.569	12.0	4.0	2.069672e-003	0.96	6.24
-30.900	26.819	12.0	4.0	1.082092e-003	1.17	6.26
-30.650	26.819	12.0	4.0	1.270161e-003	1.09	6.26
-30.400	26.819	12.0	4.0	1.747511e-003	1.05	6.26
-30.150	26.819	12.0	4.0	1.418286e-003	1.01	6.24
-29.900	26.819	12.0	4.0	1.472305e-003	1.01	6.24
-29.650	26.819	12.0	4.0	1.861096e-003	1.00	6.24
-29.400	26.819	12.0	4.0	1.941709e-003	0.98	6.24
-29.150	26.819	12.0	4.0	2.399616e-003	0.99	6.24
-28.900	26.819	12.0	4.0	1.781979e-003	0.98	6.24
-28.650	26.819	12.0	4.0	2.643073e-003	0.94	6.23
-28.400	26.819	12.0	4.0	2.480550e-003	0.94	6.23
-31.400	27.069	12.0	4.0	1.942060e-003	0.96	6.25
-31.150	27.069	12.0	4.0	1.946774e-003	0.96	6.26
-30.900	27.069	12.0	4.0	1.476680e-003	1.06	6.26
-30.650	27.069	12.0	4.0	2.037005e-003	1.03	6.26
-30.400	27.069	12.0	4.0	1.834763e-003	1.01	6.26
-30.150	27.069	12.0	4.0	1.902311e-003	1.00	6.24
-29.900	27.069	12.0	4.0	1.919520e-003	1.00	6.24
-29.650	27.069	12.0	4.0	1.924337e-003	1.00	6.24
-29.400	27.069	12.0	4.0	1.982586e-003	1.00	6.24
-29.150	27.069	12.0	4.0	2.190069e-003	1.00	6.24
-28.900	27.069	12.0	4.0	1.692751e-003	0.99	6.24
-28.650	27.069	12.0	4.0	2.443943e-003	0.94	6.23
-28.400	27.069	12.0	4.0	2.197619e-003	0.95	6.23
-28.150	27.069	12.0	4.0	2.887439e-003	0.94	6.23
-31.650	27.319	12.0	4.0	1.409235e-003	0.96	6.20
-31.400	27.319	12.0	4.0	1.101747e-003	1.12	6.20
-31.150	27.319	12.0	4.0	1.344225e-003	1.06	6.26
-30.900	27.319	12.0	4.0	1.863347e-003	1.06	6.26
-30.650	27.319	12.0	4.0	2.128020e-003	1.03	6.26
-30.400	27.319	12.0	4.0	1.909126e-003	1.00	6.26
-30.150	27.319	12.0	4.0	1.997301e-003	1.00	6.24
-29.900	27.319	12.0	4.0	2.002364e-003	1.00	6.24
-29.650	27.319	12.0	4.0	1.857130e-003	1.01	6.24
-29.400	27.319	12.0	4.0	1.873854e-003	1.02	6.24
-29.150	27.319	12.0	4.0	1.991038e-003	1.01	6.24
-28.900	27.319	12.0	4.0	1.253436e-003	1.02	6.24
-28.650	27.319	12.0	4.0	2.443943e-003	0.94	6.23
-28.400	27.319	12.0	4.0	2.253730e-003	0.93	6.23
-28.150	27.319	12.0	4.0	2.887439e-003	0.94	6.23
-27.900	27.319	12.0	4.0	2.941053e-003	0.93	6.23
-27.650	27.319	12.0	4.0	3.298132e-003	0.91	6.23
-31.900	27.569	12.0	4.0	5.371393e-004	0.96	6.20
-31.650	27.569	12.0	4.0	1.708204e-003	0.96	6.20
-31.400	27.569	12.0	4.0	1.242598e-003	1.14	6.20
-31.150	27.569	12.0	4.0	1.718253e-003	1.06	6.20
-30.900	27.569	12.0	4.0	1.977990e-003	1.06	6.25
-30.650	27.569	12.0	4.0	1.990233e-003	1.01	6.25
-30.400	27.569	12.0	4.0	1.995381e-003	1.01	6.25
-30.150	27.569	12.0	4.0	2.005164e-003	1.01	6.25
-29.900	27.569	12.0	4.0	2.002364e-003	1.00	6.24
-29.650	27.569	12.0	4.0	2.007389e-003	1.00	6.24
-29.400	27.569	12.0	4.0	1.947620e-003	1.02	6.24
-29.150	27.569	12.0	4.0	1.970806e-003	1.01	6.24
-28.900	27.569	12.0	4.0	1.253436e-003	1.02	6.24
-28.650	27.569	12.0	4.0	2.443943e-003	0.94	6.23
-28.400	27.569	12.0	4.0	2.349185e-003	0.94	6.23
-28.150	27.569	12.0	4.0	2.939261e-003	0.91	6.23
-27.900	27.569	12.0	4.0	2.611897e-003	0.95	6.23
-27.650	27.569	12.0	4.0	2.813989e-003	0.93	6.20
-32.150	27.819	12.0	4.0	2.678348e-004	0.96	6.20
-31.900	27.819	12.0	4.0	2.685696e-004	0.96	6.20
-31.650	27.819	12.0	4.0	9.293394e-004	1.13	6.20
-31.400	27.819	12.0	4.0	1.525204e-003	1.08	6.20
-31.150	27.819	12.0	4.0	1.819225e-003	1.06	6.20
-30.900	27.819	12.0	4.0	1.981308e-003	1.06	6.20
-30.650	27.819	12.0	4.0	1.990233e-003	1.01	6.25
-30.400	27.819	12.0	4.0	2.080236e-003	1.01	6.25
-30.150	27.819	12.0	4.0	2.085760e-003	1.01	6.24

-29.900	27.819	12.0	4.0	2.091047e-003	1.01	6.24
-29.650	27.819	12.0	4.0	2.174806e-003	0.99	6.24
-29.400	27.819	12.0	4.0	2.158869e-003	0.98	6.24
-29.150	27.819	12.0	4.0	2.212598e-003	0.99	6.24
-28.900	27.819	12.0	4.0	1.441498e-003	1.00	6.24
-28.650	27.819	12.0	4.0	1.753581e-003	0.98	6.23
-28.400	27.819	12.0	4.0	2.201084e-003	0.95	6.23
-28.150	27.819	12.0	4.0	2.034750e-003	0.96	6.20
-27.900	27.819	12.0	4.0	2.596012e-003	0.95	6.20
-27.650	27.819	12.0	4.0	2.599247e-003	0.95	6.20
-27.400	27.819	12.0	4.0	3.612164e-003	0.92	6.20
-32.150	28.069	12.0	4.0	2.678348e-004	0.96	6.20
-31.900	28.069	12.0	4.0	2.685696e-004	0.96	6.20
-31.650	28.069	12.0	4.0	5.145564e-004	1.17	6.20
-31.400	28.069	12.0	4.0	1.376325e-003	1.05	6.20
-31.150	28.069	12.0	4.0	1.819225e-003	1.06	6.20
-30.900	28.069	12.0	4.0	1.981308e-003	1.06	6.20
-30.650	28.069	12.0	4.0	2.048231e-003	1.01	6.20
-30.400	28.069	12.0	4.0	2.053529e-003	1.01	6.20
-30.150	28.069	12.0	4.0	2.293914e-003	0.99	6.20
-29.900	28.069	12.0	4.0	2.691248e-003	0.99	6.24
-29.650	28.069	12.0	4.0	2.698002e-003	0.99	6.24
-29.400	28.069	12.0	4.0	2.582441e-003	0.99	6.24
-29.150	28.069	12.0	4.0	2.044854e-003	1.02	6.25
-28.900	28.069	12.0	4.0	1.270392e-003	1.00	6.25
-28.650	28.069	12.0	4.0	1.089770e-003	1.02	6.20
-28.400	28.069	12.0	4.0	1.650318e-003	0.98	6.20
-28.150	28.069	12.0	4.0	1.424424e-003	1.02	6.20
-27.900	28.069	12.0	4.0	2.404298e-003	0.97	6.20
-27.650	28.069	12.0	4.0	2.694165e-003	0.93	6.20
-27.400	28.069	12.0	4.0	2.230842e-003	0.94	6.20
-27.150	28.069	12.0	4.0	3.522157e-003	0.94	6.20
-32.400	28.319	12.0	4.0	2.670949e-004	0.96	6.20
-32.150	28.319	12.0	4.0	2.678348e-004	0.96	6.20
-31.900	28.319	12.0	4.0	4.700735e-004	0.96	6.20
-31.650	28.319	12.0	4.0	4.588792e-004	1.16	6.20
-31.400	28.319	12.0	4.0	1.376325e-003	1.05	6.20
-31.150	28.319	12.0	4.0	1.819225e-003	1.06	6.20
-30.900	28.319	12.0	4.0	1.971654e-003	1.05	6.20
-30.650	28.319	12.0	4.0	2.048231e-003	1.01	6.20
-30.400	28.319	12.0	4.0	2.053529e-003	1.01	6.20
-30.150	28.319	12.0	4.0	2.689828e-003	0.99	6.20
-29.900	28.319	12.0	4.0	2.696647e-003	0.99	6.20
-29.650	28.319	12.0	4.0	2.703415e-003	0.99	6.20
-29.400	28.319	12.0	4.0	2.232590e-003	0.99	6.20
-29.150	28.319	12.0	4.0	1.216523e-003	1.00	6.20
-28.900	28.319	12.0	4.0	1.244202e-003	1.01	6.20
-28.650	28.319	12.0	4.0	1.026231e-003	1.02	6.20
-28.400	28.319	12.0	4.0	1.062866e-003	0.99	6.20
-28.150	28.319	12.0	4.0	1.080674e-003	1.11	6.20
-27.900	28.319	12.0	4.0	1.165403e-003	0.96	6.20
-27.650	28.319	12.0	4.0	1.153053e-003	1.03	6.20
-27.400	28.319	12.0	4.0	1.330140e-003	1.01	6.20
-27.150	28.319	12.0	4.0	3.151378e-003	0.92	6.20
-32.400	28.569	12.0	4.0	2.670949e-004	0.96	6.20
-32.150	28.569	12.0	4.0	2.678348e-004	0.96	6.20
-31.900	28.569	12.0	4.0	6.267646e-004	0.96	6.20
-31.650	28.569	12.0	4.0	4.637192e-004	1.15	6.20
-31.400	28.569	12.0	4.0	9.070665e-004	1.07	6.20
-31.150	28.569	12.0	4.0	1.519507e-003	1.04	6.20
-30.900	28.569	12.0	4.0	1.978493e-003	1.04	6.20
-30.650	28.569	12.0	4.0	1.914589e-003	1.03	6.20
-30.400	28.569	12.0	4.0	2.209890e-003	1.00	6.20
-30.150	28.569	12.0	4.0	2.689828e-003	0.99	6.20
-29.900	28.569	12.0	4.0	2.696647e-003	0.99	6.20
-29.650	28.569	12.0	4.0	2.231091e-003	1.00	6.20
-29.400	28.569	12.0	4.0	1.856097e-003	0.99	6.20
-29.150	28.569	12.0	4.0	1.262945e-003	1.00	6.20
-28.900	28.569	12.0	4.0	1.087765e-003	1.01	6.20
-28.650	28.569	12.0	4.0	9.020117e-004	1.04	6.20
-28.400	28.569	12.0	4.0	8.815108e-004	1.03	6.20
-28.150	28.569	12.0	4.0	8.196838e-004	1.14	6.20
-27.900	28.569	12.0	4.0	1.165403e-003	0.96	6.20
-27.650	28.569	12.0	4.0	5.759755e-004	0.96	6.20
-27.400	28.569	12.0	4.0	6.439643e-004	1.07	6.20
-27.150	28.569	12.0	4.0	1.162625e-003	0.96	6.39
-26.900	28.569	12.0	4.0	3.204131e-003	0.92	6.39
-32.400	28.819	12.0	4.0	2.670949e-004	0.96	6.20
-32.150	28.819	12.0	4.0	5.356696e-004	0.96	6.20

-31.900	28.819	12.0	4.0	6.267646e-004	0.96	6.20
-31.650	28.819	12.0	4.0	4.637192e-004	1.15	6.20
-31.400	28.819	12.0	4.0	6.692913e-004	1.13	6.20
-31.150	28.819	12.0	4.0	1.069725e-003	1.06	6.20
-30.900	28.819	12.0	4.0	1.115659e-003	1.05	6.20
-30.650	28.819	12.0	4.0	1.067999e-003	1.03	6.20
-30.400	28.819	12.0	4.0	2.239424e-003	0.98	6.20
-30.150	28.819	12.0	4.0	2.173250e-003	1.00	6.20
-29.900	28.819	12.0	4.0	1.856930e-003	1.00	6.20
-29.650	28.819	12.0	4.0	1.877636e-003	1.00	6.20
-29.400	28.819	12.0	4.0	1.506779e-003	0.99	6.20
-29.150	28.819	12.0	4.0	1.230995e-003	1.00	6.20
-28.900	28.819	12.0	4.0	1.136211e-003	1.00	6.20
-28.650	28.819	12.0	4.0	7.273227e-004	1.05	6.20
-28.400	28.819	12.0	4.0	1.028670e-003	0.96	6.20
-28.150	28.819	12.0	4.0	8.865205e-004	0.96	6.20
-27.900	28.819	12.0	4.0	4.889998e-004	0.96	6.39
-27.650	28.819	12.0	4.0	3.413002e-004	0.96	6.39
-27.400	28.819	12.0	4.0	5.833554e-004	0.96	6.39
-27.150	28.819	12.0	4.0	9.530549e-004	1.00	6.39
-26.900	28.819	12.0	4.0	9.859696e-004	1.00	6.39
-32.650	29.069	12.0	4.0	2.663499e-004	0.96	6.20
-32.400	29.069	12.0	4.0	5.341898e-004	0.96	6.20
-32.150	29.069	12.0	4.0	5.356696e-004	0.96	6.20
-31.900	29.069	12.0	4.0	4.700735e-004	0.96	6.20
-31.650	29.069	12.0	4.0	5.494825e-004	1.13	6.20
-31.400	29.069	12.0	4.0	8.803594e-004	1.07	6.20
-31.150	29.069	12.0	4.0	1.060478e-003	1.05	6.20
-30.900	29.069	12.0	4.0	1.252196e-003	1.01	6.20
-30.650	29.069	12.0	4.0	1.171911e-003	1.01	6.20
-30.400	29.069	12.0	4.0	1.811950e-003	0.99	6.20
-30.150	29.069	12.0	4.0	1.919308e-003	0.98	6.20
-29.900	29.069	12.0	4.0	1.668389e-003	0.96	6.20
-29.650	29.069	12.0	4.0	1.450064e-003	0.99	6.20
-29.400	29.069	12.0	4.0	1.453666e-003	0.99	6.20
-29.150	29.069	12.0	4.0	1.204687e-003	1.00	6.20
-28.900	29.069	12.0	4.0	9.649228e-004	1.02	6.20
-28.650	29.069	12.0	4.0	6.483685e-004	1.14	6.20
-28.400	29.069	12.0	4.0	8.827546e-004	0.96	6.40
-28.150	29.069	12.0	4.0	7.918930e-004	0.96	6.39
-27.900	29.069	12.0	4.0	7.937421e-004	0.96	6.39
-27.650	29.069	12.0	4.0	4.572320e-004	0.96	6.39
-27.400	29.069	12.0	4.0	6.048857e-004	1.11	6.39
-27.150	29.069	12.0	4.0	1.611524e-003	1.00	6.39
-26.900	29.069	12.0	4.0	1.564501e-003	0.99	6.39
-32.650	29.319	12.0	4.0	2.663499e-004	0.96	6.20
-32.400	29.319	12.0	4.0	5.341898e-004	0.96	6.20
-32.150	29.319	12.0	4.0	5.356696e-004	0.96	6.20
-31.900	29.319	12.0	4.0	6.267646e-004	0.96	6.20
-31.650	29.319	12.0	4.0	6.871132e-004	1.13	6.20
-31.400	29.319	12.0	4.0	7.454345e-004	1.10	6.20
-31.150	29.319	12.0	4.0	1.143152e-003	1.03	6.20
-30.900	29.319	12.0	4.0	1.252196e-003	1.01	6.20
-30.650	29.319	12.0	4.0	1.255467e-003	1.01	6.20
-30.400	29.319	12.0	4.0	1.273604e-003	0.97	6.20
-30.150	29.319	12.0	4.0	1.403126e-003	0.98	6.20
-29.900	29.319	12.0	4.0	1.330487e-003	0.98	6.20
-29.650	29.319	12.0	4.0	1.415415e-003	0.99	6.20
-29.400	29.319	12.0	4.0	1.403925e-003	0.97	6.20
-29.150	29.319	12.0	4.0	7.779365e-004	1.07	6.20
-28.900	29.319	12.0	4.0	6.261193e-004	1.10	6.20
-28.650	29.319	12.0	4.0	6.460037e-004	1.14	6.39
-28.400	29.319	12.0	4.0	7.466796e-004	0.96	6.40
-28.150	29.319	12.0	4.0	7.918227e-004	0.96	6.40
-27.900	29.319	12.0	4.0	7.936715e-004	0.96	6.40
-27.650	29.319	12.0	4.0	4.572320e-004	0.96	6.39
-27.400	29.319	12.0	4.0	1.473206e-003	1.03	6.39
-27.150	29.319	12.0	4.0	1.467641e-003	1.00	6.39
-26.900	29.319	12.0	4.0	1.564501e-003	0.99	6.39
-26.650	29.319	12.0	4.0	1.612310e-003	0.98	6.39
-32.650	29.569	12.0	4.0	2.663499e-004	0.96	6.20
-32.400	29.569	12.0	4.0	5.341898e-004	0.96	6.20
-32.150	29.569	12.0	4.0	5.356696e-004	0.96	6.20
-31.900	29.569	12.0	4.0	9.522541e-004	0.96	6.20
-31.650	29.569	12.0	4.0	8.600169e-004	0.96	6.20
-31.400	29.569	12.0	4.0	9.366208e-004	1.04	6.20
-31.150	29.569	12.0	4.0	1.092164e-003	1.03	6.20
-30.900	29.569	12.0	4.0	1.146168e-003	1.03	6.20
-30.650	29.569	12.0	4.0	1.255467e-003	1.01	6.20

-30.400	29.569	12.0	4.0	1.163230e-003	0.99	6.20
-30.150	29.569	12.0	4.0	1.166209e-003	0.99	6.20
-29.900	29.569	12.0	4.0	1.411872e-003	0.99	6.20
-29.650	29.569	12.0	4.0	1.386945e-003	0.99	6.20
-29.400	29.569	12.0	4.0	1.112197e-003	1.02	6.20
-29.150	29.569	12.0	4.0	7.608151e-004	1.08	6.20
-28.900	29.569	12.0	4.0	4.743768e-004	1.17	6.40
-28.650	29.569	12.0	4.0	9.009963e-004	0.96	6.35
-28.400	29.569	12.0	4.0	7.469098e-004	0.96	6.36
-28.150	29.569	12.0	4.0	7.921210e-004	0.96	6.36
-27.900	29.569	12.0	4.0	7.941379e-004	0.96	6.34
-27.650	29.569	12.0	4.0	1.683618e-003	0.96	6.40
-27.400	29.569	12.0	4.0	1.742303e-003	1.00	6.39
-27.150	29.569	12.0	4.0	1.769065e-003	0.97	6.39
-26.900	29.569	12.0	4.0	2.402788e-003	0.95	6.39
-26.650	29.569	12.0	4.0	1.903511e-003	0.95	6.39
-32.400	29.819	12.0	4.0	2.670949e-004	0.96	6.20
-32.150	29.819	12.0	4.0	1.010734e-003	0.96	6.20
-31.900	29.819	12.0	4.0	1.013507e-003	0.96	6.20
-31.650	29.819	12.0	4.0	8.600169e-004	0.96	6.20
-31.400	29.819	12.0	4.0	8.378868e-004	1.07	6.20
-31.150	29.819	12.0	4.0	9.653252e-004	1.04	6.20
-30.900	29.819	12.0	4.0	1.033440e-003	1.04	6.20
-30.650	29.819	12.0	4.0	1.170449e-003	1.03	6.20
-30.400	29.819	12.0	4.0	1.082175e-003	1.01	6.20
-30.150	29.819	12.0	4.0	1.108629e-003	1.02	6.20
-29.900	29.819	12.0	4.0	1.083001e-003	1.03	6.20
-29.650	29.819	12.0	4.0	9.507357e-004	1.05	6.20
-29.400	29.819	12.0	4.0	8.238576e-004	1.06	6.40
-29.150	29.819	12.0	4.0	6.697987e-004	1.09	6.40
-28.900	29.819	12.0	4.0	4.747090e-004	1.17	6.35
-28.650	29.819	12.0	4.0	7.451968e-004	0.96	6.35
-28.400	29.819	12.0	4.0	7.561290e-004	0.96	6.35
-28.150	29.819	12.0	4.0	6.867802e-004	0.96	6.36
-27.900	29.819	12.0	4.0	1.113758e-003	1.15	6.35
-27.650	29.819	12.0	4.0	1.765193e-003	1.11	6.35
-27.400	29.819	12.0	4.0	2.667774e-003	0.97	6.35
-27.150	29.819	12.0	4.0	2.395033e-003	0.96	6.36
-26.900	29.819	12.0	4.0	2.529746e-003	0.94	6.41
-26.650	29.819	12.0	4.0	2.406323e-003	0.95	6.41
-32.400	30.069	12.0	4.0	2.670949e-004	0.96	6.20
-32.150	30.069	12.0	4.0	1.010734e-003	0.96	6.20
-31.900	30.069	12.0	4.0	1.013507e-003	0.96	6.20
-31.650	30.069	12.0	4.0	9.548414e-004	0.96	6.20
-31.400	30.069	12.0	4.0	7.413690e-004	1.10	6.20
-31.150	30.069	12.0	4.0	8.022135e-004	1.08	6.20
-30.900	30.069	12.0	4.0	8.717511e-004	1.07	6.20
-30.650	30.069	12.0	4.0	9.674936e-004	1.06	6.20
-30.400	30.069	12.0	4.0	9.872263e-004	1.06	6.20
-30.150	30.069	12.0	4.0	9.543310e-004	1.04	6.20
-29.900	30.069	12.0	4.0	9.254826e-004	1.04	6.20
-29.650	30.069	12.0	4.0	8.599780e-004	1.05	6.40
-29.400	30.069	12.0	4.0	6.681556e-004	1.09	6.40
-29.150	30.069	12.0	4.0	6.699895e-004	1.09	6.36
-28.900	30.069	12.0	4.0	5.225639e-004	1.15	6.36
-28.650	30.069	12.0	4.0	6.835338e-004	0.96	6.36
-28.400	30.069	12.0	4.0	6.852110e-004	0.96	6.35
-28.150	30.069	12.0	4.0	6.995631e-004	1.09	6.36
-27.900	30.069	12.0	4.0	1.758971e-003	1.11	6.37
-27.650	30.069	12.0	4.0	1.765193e-003	1.11	6.35
-27.400	30.069	12.0	4.0	2.304957e-003	1.01	6.35
-27.150	30.069	12.0	4.0	2.275660e-003	0.99	6.36
-26.900	30.069	12.0	4.0	3.206381e-003	0.92	6.36
-26.650	30.069	12.0	4.0	2.532502e-003	0.94	6.42
-32.400	30.319	12.0	4.0	2.670949e-004	0.96	6.20
-32.150	30.319	12.0	4.0	1.010734e-003	0.96	6.20
-31.900	30.319	12.0	4.0	1.013507e-003	0.96	6.20
-31.650	30.319	12.0	4.0	1.016260e-003	0.96	6.20
-31.400	30.319	12.0	4.0	9.692862e-004	0.96	6.20
-31.150	30.319	12.0	4.0	8.022135e-004	1.08	6.20
-30.900	30.319	12.0	4.0	8.388699e-004	1.07	6.20
-30.650	30.319	12.0	4.0	8.740283e-004	1.07	6.20
-30.400	30.319	12.0	4.0	9.261691e-004	1.07	6.20
-30.150	30.319	12.0	4.0	9.241260e-004	1.06	6.20
-29.900	30.319	12.0	4.0	8.553289e-004	1.05	6.41
-29.650	30.319	12.0	4.0	7.095394e-004	1.08	6.42
-29.400	30.319	12.0	4.0	6.680701e-004	1.09	6.42
-29.150	30.319	12.0	4.0	6.699895e-004	1.09	6.36
-28.900	30.319	12.0	4.0	6.818911e-004	0.96	6.36

-28.650	30.319	12.0	4.0	6.835338e-004	0.96	6.36
-28.400	30.319	12.0	4.0	5.399681e-004	1.16	6.36
-28.150	30.319	12.0	4.0	5.497890e-004	1.15	6.37
-27.900	30.319	12.0	4.0	1.758971e-003	1.11	6.37
-27.650	30.319	12.0	4.0	2.601671e-003	1.05	6.36
-27.400	30.319	12.0	4.0	3.074702e-003	0.98	6.37
-27.150	30.319	12.0	4.0	2.883187e-003	0.97	6.37
-26.900	30.319	12.0	4.0	2.889639e-003	0.97	6.37
-26.650	30.319	12.0	4.0	3.059629e-003	0.94	6.37
-32.400	30.569	12.0	4.0	2.670949e-004	0.96	6.20
-32.150	30.569	12.0	4.0	1.010734e-003	0.96	6.20
-31.900	30.569	12.0	4.0	1.013507e-003	0.96	6.20
-31.650	30.569	12.0	4.0	1.016260e-003	0.96	6.20
-31.400	30.569	12.0	4.0	9.692862e-004	0.96	6.20
-31.150	30.569	12.0	4.0	9.718687e-004	0.96	6.20
-30.900	30.569	12.0	4.0	8.302598e-004	1.09	6.20
-30.650	30.569	12.0	4.0	8.686164e-004	1.07	6.20
-30.400	30.569	12.0	4.0	9.005760e-004	1.07	6.20
-30.150	30.569	12.0	4.0	8.910383e-004	1.07	6.43
-29.900	30.569	12.0	4.0	8.013452e-004	1.09	6.43
-29.650	30.569	12.0	4.0	8.070210e-004	1.06	6.42
-29.400	30.569	12.0	4.0	6.683459e-004	1.09	6.36
-29.150	30.569	12.0	4.0	6.151935e-004	1.11	6.36
-28.900	30.569	12.0	4.0	6.818911e-004	0.96	6.36
-28.650	30.569	12.0	4.0	4.935255e-004	1.18	6.36
-28.400	30.569	12.0	4.0	6.288581e-004	1.12	6.36
-28.150	30.569	12.0	4.0	7.589249e-004	1.12	6.37
-27.900	30.569	12.0	4.0	2.416684e-003	1.08	6.37
-27.650	30.569	12.0	4.0	2.609370e-003	1.05	6.38
-27.400	30.569	12.0	4.0	2.939263e-003	1.01	6.37
-27.150	30.569	12.0	4.0	3.081657e-003	0.98	6.37
-26.900	30.569	12.0	4.0	2.720933e-003	0.98	6.37
-26.650	30.569	12.0	4.0	2.897817e-003	0.96	6.37
-32.150	30.819	12.0	4.0	1.010734e-003	0.96	6.20
-31.900	30.819	12.0	4.0	1.013507e-003	0.96	6.20
-31.650	30.819	12.0	4.0	1.016260e-003	0.96	6.20
-31.400	30.819	12.0	4.0	9.692862e-004	0.96	6.20
-31.150	30.819	12.0	4.0	9.718687e-004	0.96	6.20
-30.900	30.819	12.0	4.0	9.744327e-004	0.96	6.20
-30.650	30.819	12.0	4.0	7.943715e-004	1.09	6.20
-30.400	30.819	12.0	4.0	7.847799e-004	1.09	6.43
-30.150	30.819	12.0	4.0	7.282737e-004	1.11	6.43
-29.900	30.819	12.0	4.0	7.301199e-004	1.11	6.43
-29.650	30.819	12.0	4.0	6.725234e-004	1.12	6.42
-29.400	30.819	12.0	4.0	9.913605e-004	0.96	6.36
-29.150	30.819	12.0	4.0	5.995144e-004	1.15	6.36
-28.900	30.819	12.0	4.0	7.913018e-004	0.96	6.36
-28.650	30.819	12.0	4.0	5.438549e-004	0.96	6.36
-28.400	30.819	12.0	4.0	5.666280e-004	1.13	6.36
-28.150	30.819	12.0	4.0	7.934466e-004	1.11	6.37
-27.900	30.819	12.0	4.0	2.603355e-003	1.05	6.38
-27.650	30.819	12.0	4.0	2.609370e-003	1.05	6.38
-27.400	30.819	12.0	4.0	2.691920e-003	1.04	6.38
-27.150	30.819	12.0	4.0	2.960423e-003	1.01	6.37
-26.900	30.819	12.0	4.0	3.221511e-003	0.97	6.37
-26.650	30.819	12.0	4.0	2.782763e-003	0.97	6.37
-32.150	31.069	12.0	4.0	9.708510e-004	0.96	6.20
-31.900	31.069	12.0	4.0	1.013507e-003	0.96	6.20
-31.650	31.069	12.0	4.0	1.016260e-003	0.96	6.20
-31.400	31.069	12.0	4.0	9.692862e-004	0.96	6.20
-31.150	31.069	12.0	4.0	9.718687e-004	0.96	6.20
-30.900	31.069	12.0	4.0	9.744327e-004	0.96	6.20
-30.650	31.069	12.0	4.0	7.412609e-004	1.13	6.20
-30.400	31.069	12.0	4.0	7.264136e-004	1.11	6.43
-30.150	31.069	12.0	4.0	6.610174e-004	1.15	6.43
-29.900	31.069	12.0	4.0	6.626931e-004	1.15	6.43
-29.650	31.069	12.0	4.0	8.811830e-004	0.96	6.42
-29.400	31.069	12.0	4.0	8.824563e-004	0.96	6.36
-29.150	31.069	12.0	4.0	5.862178e-004	1.16	6.36
-28.900	31.069	12.0	4.0	5.210355e-004	0.96	6.36
-28.650	31.069	12.0	4.0	3.887889e-004	1.19	6.36
-28.400	31.069	12.0	4.0	7.624983e-004	1.08	6.37
-28.150	31.069	12.0	4.0	2.082190e-003	1.04	6.38
-27.900	31.069	12.0	4.0	2.603355e-003	1.05	6.38
-27.650	31.069	12.0	4.0	2.609370e-003	1.05	6.38
-27.400	31.069	12.0	4.0	2.691920e-003	1.04	6.38
-27.150	31.069	12.0	4.0	2.779499e-003	1.04	6.38
-26.900	31.069	12.0	4.0	2.911486e-003	1.01	6.38
-32.150	31.319	12.0	4.0	1.093851e-003	0.96	6.20

-31.900	31.319	12.0	4.0	9.735146e-004	0.96	6.20
-31.650	31.319	12.0	4.0	1.016260e-003	0.96	6.20
-31.400	31.319	12.0	4.0	9.692862e-004	0.96	6.20
-31.150	31.319	12.0	4.0	9.718687e-004	0.96	6.20
-30.900	31.319	12.0	4.0	9.744327e-004	0.96	6.20
-30.650	31.319	12.0	4.0	7.289671e-004	1.13	6.46
-30.400	31.319	12.0	4.0	9.980530e-004	0.96	6.45
-30.150	31.319	12.0	4.0	6.598630e-004	1.15	6.45
-29.900	31.319	12.0	4.0	6.624018e-004	1.15	6.44
-29.650	31.319	12.0	4.0	8.813279e-004	0.96	6.43
-29.400	31.319	12.0	4.0	8.826144e-004	0.96	6.37
-29.150	31.319	12.0	4.0	5.198672e-004	0.96	6.37
-28.900	31.319	12.0	4.0	5.947204e-004	1.15	6.37
-28.650	31.319	12.0	4.0	7.511589e-004	1.09	6.37
-28.400	31.319	12.0	4.0	9.067328e-004	1.06	6.37
-28.150	31.319	12.0	4.0	2.082190e-003	1.04	6.38
-27.900	31.319	12.0	4.0	2.163744e-003	1.02	6.38
-27.650	31.319	12.0	4.0	3.357265e-003	1.02	6.38
-27.400	31.319	12.0	4.0	2.773226e-003	1.04	6.38
-27.150	31.319	12.0	4.0	2.779499e-003	1.04	6.38
-26.900	31.319	12.0	4.0	2.927960e-003	1.02	6.38
-31.900	31.569	12.0	4.0	1.096852e-003	0.96	6.20
-31.650	31.569	12.0	4.0	9.761596e-004	0.96	6.20
-31.400	31.569	12.0	4.0	9.787860e-004	0.96	6.20
-31.150	31.569	12.0	4.0	9.386241e-004	0.96	6.20
-30.900	31.569	12.0	4.0	9.411004e-004	0.96	6.20
-30.650	31.569	12.0	4.0	9.297855e-004	0.96	6.46
-30.400	31.569	12.0	4.0	9.976910e-004	0.96	6.46
-30.150	31.569	12.0	4.0	1.000246e-003	0.96	6.46
-29.900	31.569	12.0	4.0	8.794044e-004	0.96	6.45
-29.650	31.569	12.0	4.0	8.813279e-004	0.96	6.43
-29.400	31.569	12.0	4.0	6.528358e-004	1.13	6.37
-29.150	31.569	12.0	4.0	5.932764e-004	1.15	6.37
-28.900	31.569	12.0	4.0	6.417567e-004	1.13	6.37
-28.650	31.569	12.0	4.0	7.634909e-004	1.11	6.37
-28.400	31.569	12.0	4.0	7.649811e-004	1.11	6.38
-28.150	31.569	12.0	4.0	2.116745e-003	1.02	6.38
-27.900	31.569	12.0	4.0	2.218979e-003	1.02	6.38
-27.650	31.569	12.0	4.0	2.168743e-003	1.02	6.38
-27.400	31.569	12.0	4.0	3.453415e-003	1.02	6.39
-27.150	31.569	12.0	4.0	2.921423e-003	1.02	6.38
-26.900	31.569	12.0	4.0	3.077571e-003	1.00	6.38
-31.650	31.819	12.0	4.0	1.099832e-003	0.96	6.20
-31.400	31.819	12.0	4.0	9.787860e-004	0.96	6.20
-31.150	31.819	12.0	4.0	9.813938e-004	0.96	6.20
-30.900	31.819	12.0	4.0	9.411004e-004	0.96	6.20
-30.650	31.819	12.0	4.0	9.290727e-004	0.96	6.48
-30.400	31.819	12.0	4.0	9.973388e-004	0.96	6.47
-30.150	31.819	12.0	4.0	1.123386e-003	0.96	6.47
-29.900	31.819	12.0	4.0	1.126064e-003	0.96	6.46
-29.650	31.819	12.0	4.0	8.572940e-004	0.96	6.44
-29.400	31.819	12.0	4.0	6.137031e-004	0.96	6.37
-29.150	31.819	12.0	4.0	8.941138e-004	0.96	6.37
-28.900	31.819	12.0	4.0	6.390790e-004	1.15	6.37
-28.650	31.819	12.0	4.0	6.406186e-004	1.15	6.37
-28.400	31.819	12.0	4.0	7.649811e-004	1.11	6.38
-28.150	31.819	12.0	4.0	1.504653e-003	1.03	6.38
-27.900	31.819	12.0	4.0	2.218979e-003	1.02	6.38
-27.650	31.819	12.0	4.0	2.354305e-003	1.00	6.39
-27.400	31.819	12.0	4.0	2.394180e-003	0.99	6.39
-27.150	31.819	12.0	4.0	3.870626e-003	0.98	6.39
-31.400	32.069	12.0	4.0	1.102792e-003	0.96	6.20
-31.150	32.069	12.0	4.0	1.105730e-003	0.96	6.20
-30.900	32.069	12.0	4.0	1.108647e-003	0.96	6.20
-30.650	32.069	12.0	4.0	1.088630e-003	0.96	6.50
-30.150	32.069	12.0	4.0	3.744619e-004	0.96	6.47
-29.900	32.069	12.0	4.0	3.753546e-004	0.96	6.46
-29.650	32.069	12.0	4.0	4.812924e-004	0.96	6.46
-29.400	32.069	12.0	4.0	9.636779e-004	0.96	6.37
-29.150	32.069	12.0	4.0	9.660477e-004	0.96	6.37
-28.900	32.069	12.0	4.0	6.390790e-004	1.15	6.37
-28.650	32.069	12.0	4.0	6.406186e-004	1.15	6.37
-28.400	32.069	12.0	4.0	6.947732e-004	1.13	6.38
-28.150	32.069	12.0	4.0	1.312256e-003	1.07	6.39
-27.900	32.069	12.0	4.0	2.120565e-003	1.02	6.39
-27.650	32.069	12.0	4.0	2.361119e-003	0.99	6.39
-27.400	32.069	12.0	4.0	2.577251e-003	0.97	6.39
-27.150	32.069	12.0	4.0	2.543593e-003	0.97	6.39
-29.900	32.319	12.0	4.0	3.754112e-004	0.96	6.47

-29.650	32.319	12.0	4.0	4.813549e-004	0.96	6.47
-29.400	32.319	12.0	4.0	9.004675e-004	0.96	6.38
-29.150	32.319	12.0	4.0	9.660477e-004	0.96	6.37
-28.900	32.319	12.0	4.0	8.962901e-004	0.96	6.37
-28.650	32.319	12.0	4.0	8.701819e-004	0.96	6.39
-28.400	32.319	12.0	4.0	8.722567e-004	0.96	6.39
-28.150	32.319	12.0	4.0	6.960929e-004	1.13	6.39
-27.900	32.319	12.0	4.0	1.315320e-003	1.07	6.39
-27.650	32.319	12.0	4.0	2.270045e-003	0.99	6.39
-27.400	32.319	12.0	4.0	2.451780e-003	0.99	6.39
-29.900	32.569	12.0	4.0	5.850599e-004	0.96	6.50
-29.650	32.569	12.0	4.0	5.863954e-004	0.96	6.48
-29.400	32.569	12.0	4.0	1.004642e-003	0.96	6.39
-29.150	32.569	12.0	4.0	9.026819e-004	0.96	6.38
-28.900	32.569	12.0	4.0	8.386501e-004	0.96	6.40
-28.650	32.569	12.0	4.0	8.410470e-004	0.96	6.39
-28.400	32.569	12.0	4.0	8.722567e-004	0.96	6.39
-28.150	32.569	12.0	4.0	8.743148e-004	0.96	6.39
-27.900	32.569	12.0	4.0	1.315320e-003	1.07	6.39
-27.650	32.569	12.0	4.0	1.444069e-003	1.03	6.39
-29.900	32.819	12.0	4.0	5.850599e-004	0.96	6.50
-29.650	32.819	12.0	4.0	5.863954e-004	0.96	6.48
-29.400	32.819	12.0	4.0	1.000413e-003	0.96	6.48
-29.150	32.819	12.0	4.0	9.022455e-004	0.96	6.39
-28.900	32.819	12.0	4.0	9.040156e-004	0.96	6.40
-28.650	32.819	12.0	4.0	8.406705e-004	0.96	6.40
-28.400	32.819	12.0	4.0	8.430523e-004	0.96	6.39
-28.150	32.819	12.0	4.0	8.450416e-004	0.96	6.39
-27.900	32.819	12.0	4.0	8.470147e-004	0.96	6.39
-29.900	33.069	12.0	4.0	5.850599e-004	0.96	6.50
-29.650	33.069	12.0	4.0	5.865282e-004	0.96	6.50
-29.400	33.069	12.0	4.0	1.000413e-003	0.96	6.48
-29.150	33.069	12.0	4.0	1.005103e-003	0.96	6.43
-28.900	33.069	12.0	4.0	9.040156e-004	0.96	6.40
-28.650	33.069	12.0	4.0	8.399473e-004	0.96	6.42
-28.400	33.069	12.0	4.0	8.426749e-004	0.96	6.40
-28.150	33.069	12.0	4.0	8.446633e-004	0.96	6.40
-29.650	33.319	12.0	4.0	5.868470e-004	0.96	6.55
-29.400	33.319	12.0	4.0	5.883049e-004	0.96	6.55
-29.150	33.319	12.0	4.0	9.995325e-004	0.96	6.57
-28.900	33.319	12.0	4.0	1.006173e-003	0.96	6.46
-28.650	33.319	12.0	4.0	1.010462e-003	0.96	6.42
-29.650	33.569	12.0	4.0	5.871476e-004	0.96	6.60
-29.400	33.569	12.0	4.0	5.886063e-004	0.96	6.60

Appendix D

Applied Ground Motion Prediction Equations

Ground Motion Prediction Equation #1

AB2006: ATKINSON-BOORE (BSSA, vol.96, pp.2181-2205, 2006)

```
ln[a(f)] = c1 + c2*mag + c3*mag^2 + (c4 + c5*mag)*f1 + (c6 + c7*mag)*f2 +
             (c8 + c9*mag)*f0 + c10*r + p*SD

   WHERE:

     a          = MEDIAN VALUE, HARD ROCK, AVERAGE HORIZONTAL COMPONENT PGA/ARS [g]
     f          = GROUND MOTION FREQUENCY. IF a = PGA, f = 99.9 [Hz]
     mag        = EARTHQUAKE MAGNITUDE Mw
     r          = HYPOCENTRAL DISTANCE (CLOSEST DISTANCE TO THE FAULT) [KM]
     f0         = MAX[log10(r0/r),0], r0 = 10 KM
     f1         = MIN[log10(r/r1],    r1 = 70 KM
     f2         = MAX[log10(r/r2),0], r2 = 140 KM
     p          = 0. IF p = 1, ln(a) = MEAN[ln(a)] + SD[ln(a)]
     c1,...,c10 = COEFFICIENTS; SD OF PREDICTED ln(a) = 0.69
```

ATTENUATION COEFFICIENTS

Freq.(Hz)	c1	c2	c3	c4	c5	c6	c7	c8	c9	c10
0.2	-5.41	1.710	-0.0901	-2.54	0.227	-1.270	0.116	0.979	-0.1770	-0.0002
0.3	-5.79	1.920	-0.1070	-2.44	0.211	-1.160	0.102	1.010	-0.1820	-0.0002
0.4	-6.17	2.210	-0.1350	-2.30	0.190	-0.986	0.079	0.968	-0.1770	-0.0003
0.5	-6.18	2.300	-0.1440	-2.22	0.177	-0.937	0.071	0.952	-0.1770	-0.0003
0.8	-5.72	2.320	-0.1510	-2.10	0.157	-0.820	0.052	0.856	-0.1660	-0.0004
1.0	-5.27	2.260	-0.1480	-2.07	0.150	-0.813	0.047	0.826	-0.1620	-0.0005
2.0	-3.22	1.830	-0.1200	-2.02	0.134	-0.813	0.044	0.884	-0.1750	-0.0008
2.5	-2.44	1.650	-0.1080	-2.05	0.136	-0.843	0.045	0.739	-0.1560	-0.0009
4.0	-1.12	1.340	-0.0872	-2.08	0.135	-0.971	0.056	0.614	0.1430	-0.0011
5.0	-0.61	1.230	-0.0789	-2.09	0.131	-1.120	0.068	0.606	-0.1460	-0.0011
8.0	0.21	1.050	-0.0666	-2.15	0.130	-1.610	0.105	0.427	-0.1300	-0.0012
10.0	0.48	1.020	-0.0640	-2.20	0.127	-2.010	0.133	0.337	-0.1270	-0.0010
20.0	1.11	0.972	-0.0620	-2.47	0.128	-3.390	0.214	-0.139	-0.0984	-0.0003
25.2	1.26	0.968	-0.0623	-2.58	0.132	-3.640	0.228	-0.351	-0.0813	-0.0001
40.0	1.52	0.960	-0.0635	-2.81	0.146	-3.650	0.236	-0.654	-0.0550	-0.0000
PGA	0.91	0.983	-0.0660	-2.70	0.159	-2.800	0.212	-0.301	-0.0653	-0.0004

Ground Motion Prediction Equation #2

```
    BA2008: BOORE-ATKINSON NGA (Earthquake Spectra, vol.24, pp.99-138, 2008)
   =========================================================================

             ln[a(f)] = F_M(mag) + F_D(r_JB) + p*SD

   WHERE:

     F_M, and F_D are mag scaling and distance function
     f          = GROUND MOTION FREQUENCY. IF a = PGA, f = 99.9 [Hz]
     mag        = EARTHQUAKE MAGNITUDE Mw
     r_JB       = JB DISTANCE (CLOSEST DISTANCE TO THE FAULT) [KM]
     p          = 0. IF p = 1, ln(a) = MEAN[ln(a)] + SD[ln(a)]

For details see: Boore D.M. and G.M. Atkinson (2008). "Ground motion prediction
equation for the average horizontal component of PGA, PGV, and periods between
0.01s
and 10.0s.", Earthquake Spectra, vol.24, pp.99-138
```

Appendix E

Results of PSHA

Tabulated values of mean activity rate, return periods and probability of exceedance in 1, 50, 100 and 1,000 years for specified values of PGA

GMPE: AB06

```
=====================================
 File       : info_hazard_AB06.txt
 Created on : 11-Jul-2012 13:18:09
=====================================

 PROBABILISTIC SEISMIC HAZARD ASSESSMENT FOR A SELECTED SITE
             BY THE CORNELL-McGUIRE PROCEDURE
 ============================================================

 THE APPLIED METHODOLOGY IS DESCRIBED IN THE DOCUMENT:

    "Recommendation for Probabilistic Seismic Hazard Analysis:
     Guidance on Uncertainty and Use of Experts",

     Prepared by:

     Senior Seismic Hazard Analysis Committee (SSHAC),
     R.J. Budnitz (Chairman), G. Apostolakis, D.M. Boore, L.S. Cluff,
     K.J. Coppersmith, C.A. Cornell, and P.A. Morris.

     Lawrence Livermore National Laboratory.

     Prepared for:

     U.S. Nuclear Regulatory Commission, U.S. Department of Energy and
     Electric Power Research Institute.

     NUREG/CR-6372, UCRL-ID-122160, vol.1, April 1997


 THE CODE REQUIRES TWO INPUT FILES:

   FILE CONTAINING SITE-SPECIFIC INFORMATION:
   ------------------------------------------

       - Site coordinates, LATITUDE & LONGITUDE [DEG]

       - MINIMUM VALUE OF ANNUAL PROBABILITY OF EXCEEDANCE of PGA for which
         PSHA calculations are to be performed. Suggested values:
         for nuclear facilities, between 10^(-6) and 10^(-4),
         for large water reservoirs/dams between 10^(-4) and 10^(-3).

       - 3 TIME INTERVALS for which PSHA will be performed.
         Suggested values: 50, 100 and 1000 years.

       - Parameter controlling the ACCURACY of numerical integration.
         If its value = 1, the accuracy of integration is LOW,
         but computation time is SHORT.
         If its value = 2, accuracy of integration is MODERATE,
          but computation time is LONGER. If its value is 3,
          accuracy of integration is HIGHEST, but computations require
          SIGNIFICANTLY more time.

       - Parameter providing provision for increase/decrease
         of future seismicity.

       - Two parameters controlling UNCERTAINTY of the assumed seismicity model.
         First parameter controls uncertainty of b-value in the
         FREQUENCY-MAGNITUDE, Gutenberg-Richter relation.
          Second parameter controls uncertainty of the level of seismicity
         described by the mean activity rate LAMBDA.

       - Parameter controlling predicted value of Ground Motion.
         If its value is = 1, in all calculations the MEAN value of
         ln(Ground Motion) is used. If its value is = 2, the predicted,
         mean value of ln(Ground Motion) is increased by its STANDARD DEVIATION


   FILE CONTAINING INFORMATION ON SEISMIC SOURCES IN THE VICINITY OF THE SITE
   --------------------------------------------------------------------------

       Each seismic source is described by 7 parameters:

       (1) latitude [DEG]
       (2) longitude [DEG]
       (3) depth [KM] of seismic source,
```

```
       (4) minimum earthquake magnitude Mmin
       (5) Mean seismic activity rate LAMBDA
       (6) b-value of the frequency-magnitude Gutenberg-Richter relation
       (7) MAXIMUM, seismic source-characteristic EQ-e magnitude Mmax.


==========================================================================

 PROGRAM NAME     : HS_C_McG (H = Hazard; S = Site; C = Cornell; McG = McGuire)

 WRITTEN          : 15 SEP 2007 by A.K.
 REVISED          : 27 SEP 2007 by A.K.
                  : 30 SEP 2007 by A.K.
                  : 01 OCT 2007 by A.K.
                  : 20 FEB 2008 by A.K.
                  : 12 MAY 2008 by A.K.
                  : 21 JUN 2008 by A.K.
                  : 15 SEP 2009 by A.K.
                  : 28 OCT 2010 by A.K.
                  : 19 AUG 2011 by A.K.
                  : 14 OCT 2011 by A.K.

 REVISION         : 1.14

==========================================================================

 For more information, contact Dr. A.Kijko
 Natural Hazard Assessment Consultancy
 8 Birch Str. Clubview, ext.2
 Centurion  0157
 South Africa

 Phone  :  +27 (0) 829394002
 E-mail :  andrzej.kijko@up.ac.za or andrzej.kijko@gmail.com

==========================================================================


  PROBABILISTIC SEISMIC HAZARD ASSESSMENT BY CORNELL-McGUIRE PROCEDURE
 ======================================================================

     The applied approach takes into account ground motion variability
     by integrating across the scatter in the attenuation equation


 NAME OF THE SITE: uMWP1-1/RW

 ATTENUATION MODEL #3: ATKINSON & BOORE (2006)

 SITE COORDINATES (LATITUDE)                =  -29.775 [DEG]
 SITE COORDINATES (LONGITUDE)               =   29.944 [DEG]

 MINIMUM ANNUAL PROBABILITY OF EXCEEDANCE   = 1.000e-004 [DEG]

 PSHA IS CALCULATED FOR TIME INTERVALS      = 50 100 and 1000 YEARS

 ACCURACY OF NUMERICAL INTEGRATION: MEDIUM
 MAGNITUDE INTEGRATION INTERVAL    = 0.25

 PROVISION FOR INDUCED SEISMICITY: REQUIRED
 MULTIPLICATIVE FACTOR OF LAMBDA = 1

 MODEL UNCERTAINTY OF THE b-VALUE              = 25   [per cent]
 MODEL UNCERTAINTY OF THE SITE-SPECIFIC LAMBDA = 25   [per cent]

 ALL CALCULATIONS ARE PERFORMED FOR MEAN VALUE OF ln[PGA/ARS]

 NAME OF INPUT FILE WITH PARAMETERS OF SEISMIC SOURCES: ss.txt


 Max EXPECTED PGA AT THE SITE = 0.172 [g] (FROM SEISMIC SOURCE #286)


                              SEISMIC HAZARD
         ==========================================================

 PGA[g] Lambda[EQ/Y]   RP[Y]      <RP-SD RP+SD>     Pr(T = 1 50 100 1000 [Y])
```

0.010	1.51e-002	6.63e+001	<9.18e-002 1.33e+002>	0.0150	0.5296	0.7787	1.0000
0.020	4.94e-003	2.03e+002	<6.97e-001 4.04e+002>	0.0049	0.2188	0.3897	0.9928
0.030	2.42e-003	4.13e+002	<2.00e+000 8.24e+002>	0.0024	0.1140	0.2150	0.9111
0.040	1.41e-003	7.07e+002	<4.12e+000 1.41e+003>	0.0014	0.0683	0.1319	0.7571
0.050	9.17e-004	1.09e+003	<7.23e+000 2.17e+003>	0.0009	0.0448	0.0876	0.6002
0.060	6.36e-004	1.57e+003	<1.15e+001 3.13e+003>	0.0006	0.0313	0.0616	0.4707
0.070	4.63e-004	2.16e+003	<1.73e+001 4.30e+003>	0.0005	0.0229	0.0453	0.3709
0.080	3.50e-004	2.86e+003	<2.47e+001 5.69e+003>	0.0004	0.0174	0.0344	0.2954
0.090	2.72e-004	3.68e+003	<3.40e+001 7.32e+003>	0.0003	0.0135	0.0268	0.2382
0.100	2.16e-004	4.63e+003	<4.56e+001 9.21e+003>	0.0002	0.0108	0.0214	0.1944
0.110	1.75e-004	5.72e+003	<5.97e+001 1.14e+004>	0.0002	0.0087	0.0173	0.1604
0.120	1.44e-004	6.97e+003	<7.66e+001 1.39e+004>	0.0001	0.0072	0.0142	0.1337
0.130	1.19e-004	8.38e+003	<9.69e+001 1.67e+004>	0.0001	0.0059	0.0119	0.1124
0.140	1.00e-004	9.98e+003	<1.21e+002 1.98e+004>	0.0001	0.0050	0.0100	0.0953
0.150	8.49e-005	1.18e+004	<1.49e+002 2.34e+004>	0.0001	0.0042	0.0085	0.0814

UNIFORM ACCELERATION RERSPONSE SPECTRA

Return Period = 100 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
0.50	2.00	0.010
0.40	2.50	0.011
0.25	4.00	0.012
0.20	5.00	0.014
0.13	8.00	0.018
0.10	10.00	0.021
0.05	20.00	0.023
0.04	25.20	0.022
0.03	40.00	0.019
0.01	99.00	0.011

Return Period = 200 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
0.50	2.00	0.011
0.40	2.50	0.012
0.25	4.00	0.016
0.20	5.00	0.021
0.13	8.00	0.028
0.10	10.00	0.035
0.05	20.00	0.040
0.04	25.20	0.038
0.03	40.00	0.031
0.01	99.00	0.014

Return Period = 475 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
1.00	1.00	0.010
0.50	2.00	0.014
0.40	2.50	0.017
0.25	4.00	0.027
0.20	5.00	0.038
0.13	8.00	0.055
0.10	10.00	0.065
0.05	20.00	0.071
0.04	25.20	0.070
0.03	40.00	0.063
0.01	99.00	0.024

Return Period = 1000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
1.00	1.00	0.010
0.50	2.00	0.019
0.40	2.50	0.027
0.25	4.00	0.048
0.20	5.00	0.063
0.13	8.00	0.077
0.10	10.00	0.093
0.05	20.00	0.110
0.04	25.20	0.108
0.03	40.00	0.094
0.01	99.00	0.041

Return Period = 10000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
2.00	0.50	0.010
1.25	0.80	0.012
1.00	1.00	0.017
0.50	2.00	0.070
0.40	2.50	0.090
0.25	4.00	0.132
0.20	5.00	0.167
0.13	8.00	0.216
0.10	10.00	0.264
0.05	20.00	0.314
0.04	25.20	0.315
0.03	40.00	0.293
0.01	99.00	0.137

Return Period = 100000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
2.50	0.40	0.010
2.00	0.50	0.011
1.25	0.80	0.030
1.00	1.00	0.064
0.50	2.00	0.166
0.40	2.50	0.213
0.25	4.00	0.307
0.20	5.00	0.382
0.13	8.00	0.491
0.10	10.00	0.605
0.05	20.00	0.723
0.04	25.20	0.730
0.03	40.00	0.687
0.01	99.00	0.325

Return Period = 1000000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
4.00	0.25	0.010
2.50	0.40	0.012
2.00	0.50	0.024
1.25	0.80	0.077
1.00	1.00	0.125
0.50	2.00	0.324
0.40	2.50	0.414
0.25	4.00	0.589
0.20	5.00	0.736
0.13	8.00	0.936
0.10	10.00	1.153
0.05	20.00	1.375
0.04	25.20	1.387
0.03	40.00	1.308
0.01	99.00	0.622

GMPE: BA08

```
=====================================
 File       : info_hazard_BA08.txt
 Created on : 11-Jul-2012 13:31:52
=====================================

 PROBABILISTIC SEISMIC HAZARD ASSESSMENT FOR A SELECTED SITE
              BY THE CORNELL-McGUIRE PROCEDURE
 ============================================================

 THE APPLIED METHODOLOGY IS DESCRIBED IN THE DOCUMENT:

    "Recommendation for Probabilistic Seismic Hazard Analysis:
     Guidance on Uncertainty and Use of Experts",

     Prepared by:

     Senior Seismic Hazard Analysis Committee (SSHAC),
     R.J. Budnitz (Chairman), G. Apostolakis, D.M. Boore, L.S. Cluff,
     K.J. Coppersmith, C.A. Cornell, and P.A. Morris.

     Lawrence Livermore National Laboratory.

     Prepared for:

     U.S. Nuclear Regulatory Commission, U.S. Department of Energy and
     Electric Power Research Institute.

     NUREG/CR-6372, UCRL-ID-122160, vol.1, April 1997


 THE CODE REQUIRES TWO INPUT FILES:

   FILE CONTAINING SITE-SPECIFIC INFORMATION:
   ------------------------------------------

       - Site coordinates, LATITUDE & LONGITUDE [DEG]

       - MINIMUM VALUE OF ANNUAL PROBABILITY OF EXCEEDANCE of PGA for which
         PSHA calculations are to be performed. Suggested values:
         for nuclear facilities, between 10^(-6) and 10^(-4),
         for large water reservoirs/dams between 10^(-4) and 10^(-3).

       - 3 TIME INTERVALS for which PSHA will be performed.
         Suggested values: 50, 100 and 1000 years.

       - Parameter controlling the ACCURACY of numerical integration.
         If its value = 1, the accuracy of integration is LOW,
         but computation time is SHORT.
         If its value = 2, accuracy of integration is MODERATE,
          but computation time is LONGER. If its value is 3,
          accuracy of integration is HIGHEST, but computations require
          SIGNIFICANTLY more time.

       - Parameter providing provision for increase/decrease
         of future seismicity.

       - Two parameters controlling UNCERTAINTY of the assumed seismicity model.
         First parameter controls uncertainty of b-value in the
         FREQUENCY-MAGNITUDE, Gutenberg-Richter relation.
          Second parameter controls uncertainty of the level of seismicity
         described by the mean activity rate LAMBDA.

       - Parameter controlling predicted value of Ground Motion.
         If its value is = 1, in all calculations the MEAN value of
         ln(Ground Motion) is used. If its value is = 2, the predicted,
         mean value of ln(Ground Motion) is increased by its STANDARD DEVIATION


   FILE CONTAINING INFORMATION ON SEISMIC SOURCES IN THE VICINITY OF THE SITE
   --------------------------------------------------------------------------

       Each seismic source is described by 7 parameters:

       (1) latitude [DEG]
       (2) longitude [DEG]
       (3) depth [KM] of seismic source,
```

```
      (4) minimum earthquake magnitude Mmin
      (5) Mean seismic activity rate LAMBDA
      (6) b-value of the frequency-magnitude Gutenberg-Richter relation
      (7) MAXIMUM, seismic source-characteristic EQ-e magnitude Mmax.


==========================================================================

 PROGRAM NAME      : HS_C_McG (H = Hazard; S = Site; C = Cornell; McG = McGuire)

 WRITTEN           : 15 SEP 2007 by A.K.
 REVISED           : 27 SEP 2007 by A.K.
                   : 30 SEP 2007 by A.K.
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                   : 21 JUN 2008 by A.K.
                   : 15 SEP 2009 by A.K.
                   : 28 OCT 2010 by A.K.
                   : 19 AUG 2011 by A.K.
                   : 14 OCT 2011 by A.K.

 REVISION          : 1.14

==========================================================================

 For more information, contact Dr. A.Kijko
 Natural Hazard Assessment Consultancy
 8 Birch Str. Clubview, ext.2
 Centurion  0157
 South Africa

 Phone  :  +27 (0) 829394002
 E-mail :  andrzej.kijko@up.ac.za or andrzej.kijko@gmail.com

==========================================================================


  PROBABILISTIC SEISMIC HAZARD ASSESSMENT BY CORNELL-McGUIRE PROCEDURE
 ======================================================================

     The applied approach takes into account ground motion variability
     by integrating across the scatter in the attenuation equation


 NAME OF THE SITE: uMWP1-1/RW (GMPE: AB08)

 ATTENUATION MODEL #12: NGA for Active Tectonic Regions (Boore & Atkinson, 2008)


    GMPE: BOORE-ATKINSON NGA (Earthquake Spectra, vol.24, pp.99-138, 2008)
   =======================================================================

   ln[a(f)] = F_M(mag) + F_D(r_JB) + p*SD

   WHERE:

     F_M, and F_D are mag scaling and distance function
     f          = GROUND MOTION FREQUENCY. IF a = PGA, f = 99.9 [Hz]
     mag        = EARTHQUAKE MAGNITUDE Mw
     r_JB       = JB DISTANCE (CLOSEST DISTANCE TO THE FAULT) [KM]
     p          = 0. IF p = 1, ln(a) = MEAN[ln(a)] + SD[ln(a)]

  For details see: Boore D.M. and G.M. Atkinson (2008). "Ground motion prediction equation
                   for the average horizontal component of PGA, PGV, and 5
                   periods between 0.01s and 10.0s." Earthquake Spectra, vol.24, pp.99-138


 SITE COORDINATES (LATITUDE)                =  -29.775 [DEG]
 SITE COORDINATES (LONGITUDE)               =   29.944 [DEG]

 MINIMUM ANNUAL PROBABILITY OF EXCEEDANCE   = 1.000e-004 [DEG]

 PSHA IS CALCULATED FOR TIME INTERVALS      = 50 100 and 1000 YEARS

 ACCURACY OF NUMERICAL INTEGRATION: MEDIUM
 MAGNITUDE INTEGRATION INTERVAL    = 0.25

 PROVISION FOR INDUCED SEISMICITY: REQUIRED
```

MULTIPLICATIVE FACTOR OF LAMBDA = 1

MODEL UNCERTAINTY OF THE b-VALUE = 25 [per cent]
MODEL UNCERTAINTY OF THE SITE-SPECIFIC LAMBDA = 25 [per cent]

ALL CALCULATIONS ARE PERFORMED FOR MEAN VALUE OF ln[PGA/ARS]

NAME OF INPUT FILE WITH PARAMETERS OF SEISMIC SOURCES: ss.txt

Max EXPECTED PGA AT THE SITE = 0.107 [g] (FROM SEISMIC SOURCE #286)

SEISMIC HAZARD

PGA[g]	Lambda[EQ/Y]	RP[Y]	<RP-SD	RP+SD>	Pr(T = 1	50	100	1000 [Y])
0.010	1.39e-002	7.21e+001	<1.67e-001	1.44e+002>	0.0138	0.5004	0.7504	1.0000
0.020	4.55e-003	2.20e+002	<7.42e-001	4.38e+002>	0.0045	0.2036	0.3658	0.9895
0.030	2.06e-003	4.86e+002	<1.84e+000	9.70e+002>	0.0021	0.0978	0.1861	0.8724
0.040	1.09e-003	9.18e+002	<3.82e+000	1.83e+003>	0.0011	0.0530	0.1032	0.6637
0.050	6.37e-004	1.57e+003	<7.28e+000	3.13e+003>	0.0006	0.0313	0.0617	0.4711
0.060	3.99e-004	2.51e+003	<1.30e+001	5.00e+003>	0.0004	0.0197	0.0391	0.3288
0.070	2.62e-004	3.81e+003	<2.23e+001	7.60e+003>	0.0003	0.0130	0.0259	0.2307
0.080	1.79e-004	5.58e+003	<3.65e+001	1.11e+004>	0.0002	0.0089	0.0178	0.1641
0.090	1.26e-004	7.93e+003	<5.78e+001	1.58e+004>	0.0001	0.0063	0.0125	0.1185
0.100	9.10e-005	1.10e+004	<8.88e+001	2.19e+004>	0.0001	0.0045	0.0091	0.0870

UNIFORM ACCELERATION RERSPONSE SPECTRA

Return Period = 100 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
0.50	2.00	0.012
0.40	2.50	0.014
0.30	3.33	0.018
0.25	4.00	0.019
0.20	5.00	0.022
0.15	6.67	0.023
0.10	10.00	0.020
0.07	13.33	0.016
0.05	20.00	0.012
0.03	33.33	0.011
0.02	50.00	0.011
0.01	99.01	0.011

Return Period = 200 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
0.75	1.33	0.011
0.50	2.00	0.015
0.40	2.50	0.019
0.30	3.33	0.028
0.25	4.00	0.030
0.20	5.00	0.038
0.15	6.67	0.040
0.10	10.00	0.034
0.07	13.33	0.026
0.05	20.00	0.017
0.03	33.33	0.014
0.02	50.00	0.013
0.01	99.01	0.013

Return Period = 475 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
1.00	1.00	0.011
0.75	1.33	0.014
0.50	2.00	0.023
0.40	2.50	0.034
0.30	3.33	0.055
0.25	4.00	0.061
0.20	5.00	0.067
0.15	6.67	0.069
0.10	10.00	0.064
0.07	13.33	0.051
0.05	20.00	0.029
0.03	33.33	0.021
0.02	50.00	0.019
0.01	99.01	0.018

Return Period = 1000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
1.50	0.67	0.010
1.00	1.00	0.013
0.75	1.33	0.019
0.50	2.00	0.038
0.40	2.50	0.061
0.30	3.33	0.074
0.25	4.00	0.079
0.20	5.00	0.094
0.15	6.67	0.100
0.10	10.00	0.088
0.07	13.33	0.072
0.05	20.00	0.053
0.03	33.33	0.036
0.02	50.00	0.031
0.01	99.01	0.029

Return Period = 10000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
3.00	0.33	0.010
2.00	0.50	0.012
1.50	0.67	0.020
1.00	1.00	0.048
0.75	1.33	0.069
0.50	2.00	0.114
0.40	2.50	0.142
0.30	3.33	0.187
0.25	4.00	0.201
0.20	5.00	0.229
0.15	6.67	0.238
0.10	10.00	0.217
0.07	13.33	0.180
0.05	20.00	0.128
0.03	33.33	0.109
0.02	50.00	0.096
0.01	99.01	0.090

Return Period = 100000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
5.00	0.20	0.010
4.00	0.25	0.010
3.00	0.33	0.012
2.00	0.50	0.037
1.50	0.67	0.067
1.00	1.00	0.112
0.75	1.33	0.153
0.50	2.00	0.229
0.40	2.50	0.287
0.30	3.33	0.374

0.25	4.00	0.394
0.20	5.00	0.452
0.15	6.67	0.462
0.10	10.00	0.416
0.07	13.33	0.351
0.05	20.00	0.254
0.03	33.33	0.210
0.02	50.00	0.188
0.01	99.01	0.179

Return Period = 1000000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
7.50	0.13	0.010
5.00	0.20	0.010
4.00	0.25	0.012
3.00	0.33	0.033
2.00	0.50	0.083
1.50	0.67	0.128
1.00	1.00	0.203
0.75	1.33	0.274
0.50	2.00	0.405
0.40	2.50	0.499
0.30	3.33	0.643
0.25	4.00	0.673
0.20	5.00	0.767
0.15	6.67	0.773
0.10	10.00	0.697
0.07	13.33	0.590
0.05	20.00	0.425
0.03	33.33	0.347
0.02	50.00	0.319
0.01	99.01	0.307

Appendix F

Plots of hazard curves and return periods, including confidence intervals

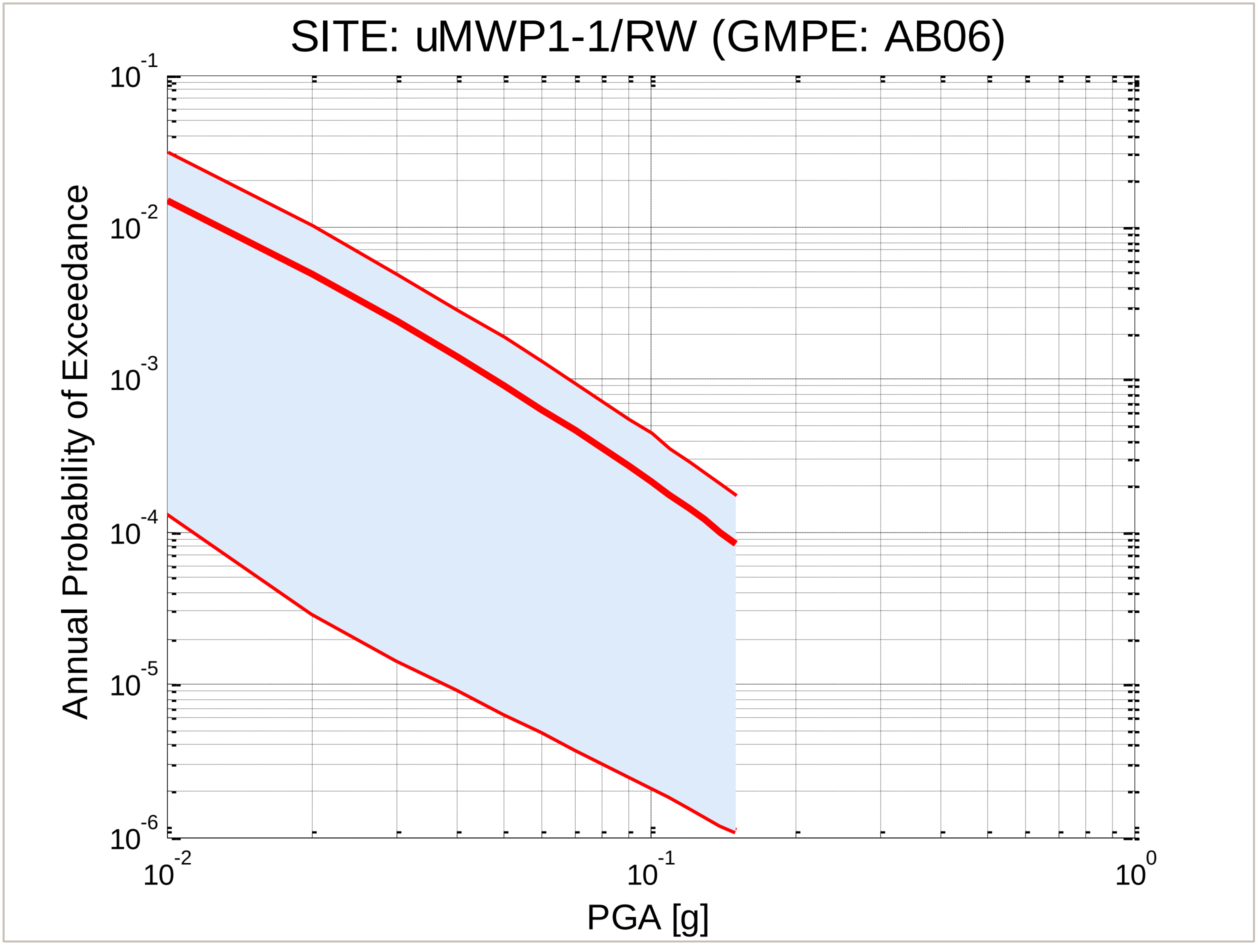

Figure 1(a) Annual probability of exceedance and its confidence intervals of the median value of horizontal PGA at the site of the dam calculated for the ground motion prediction equation AB06 (Atkinson and Boore, 2006).

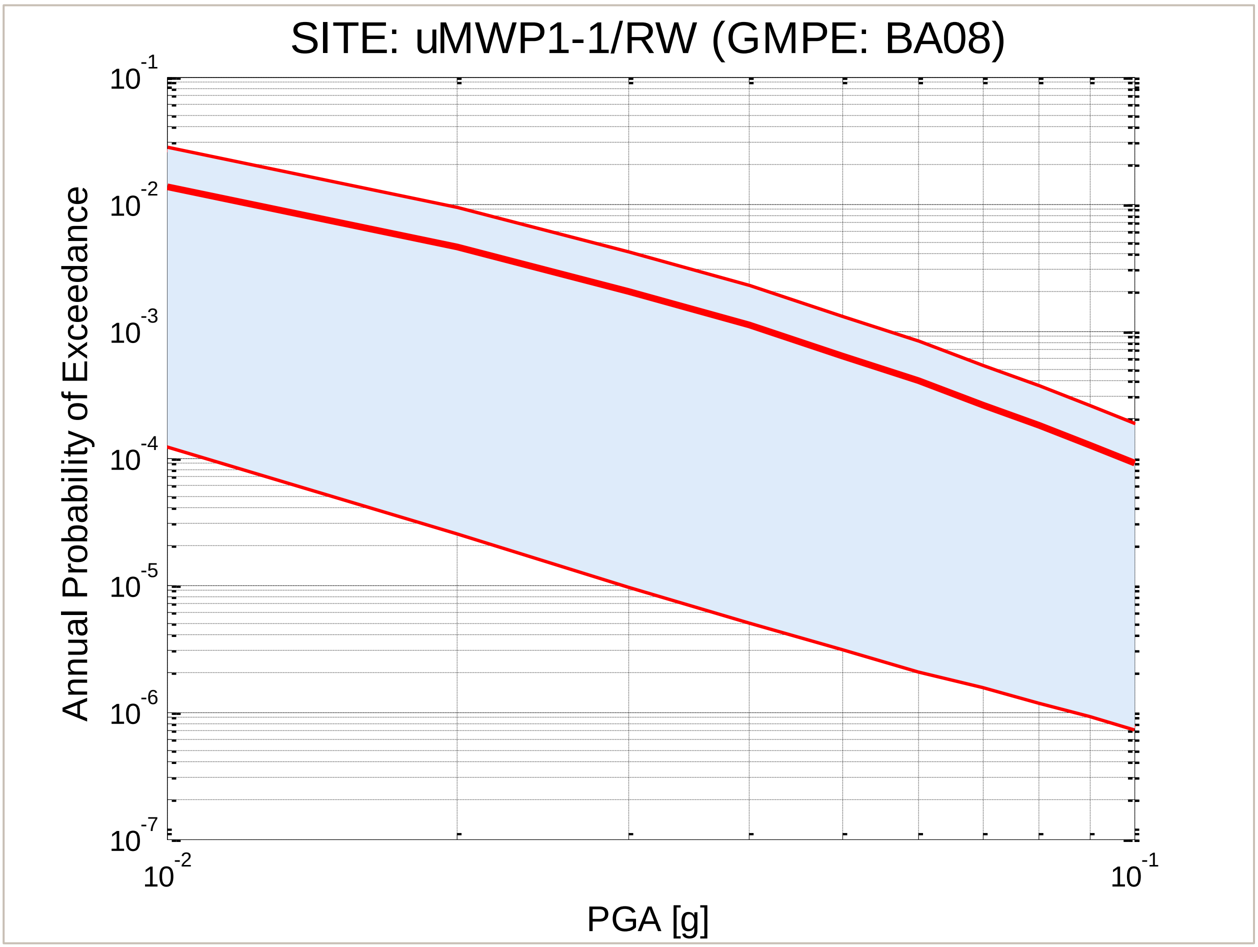

Figure 1(b) Annual probability of exceedance and its confidence intervals of median value of horizontal PGA at the site of the dam calculated for the ground motion prediction equation BA08 (Boore and Atkinson, 2008).

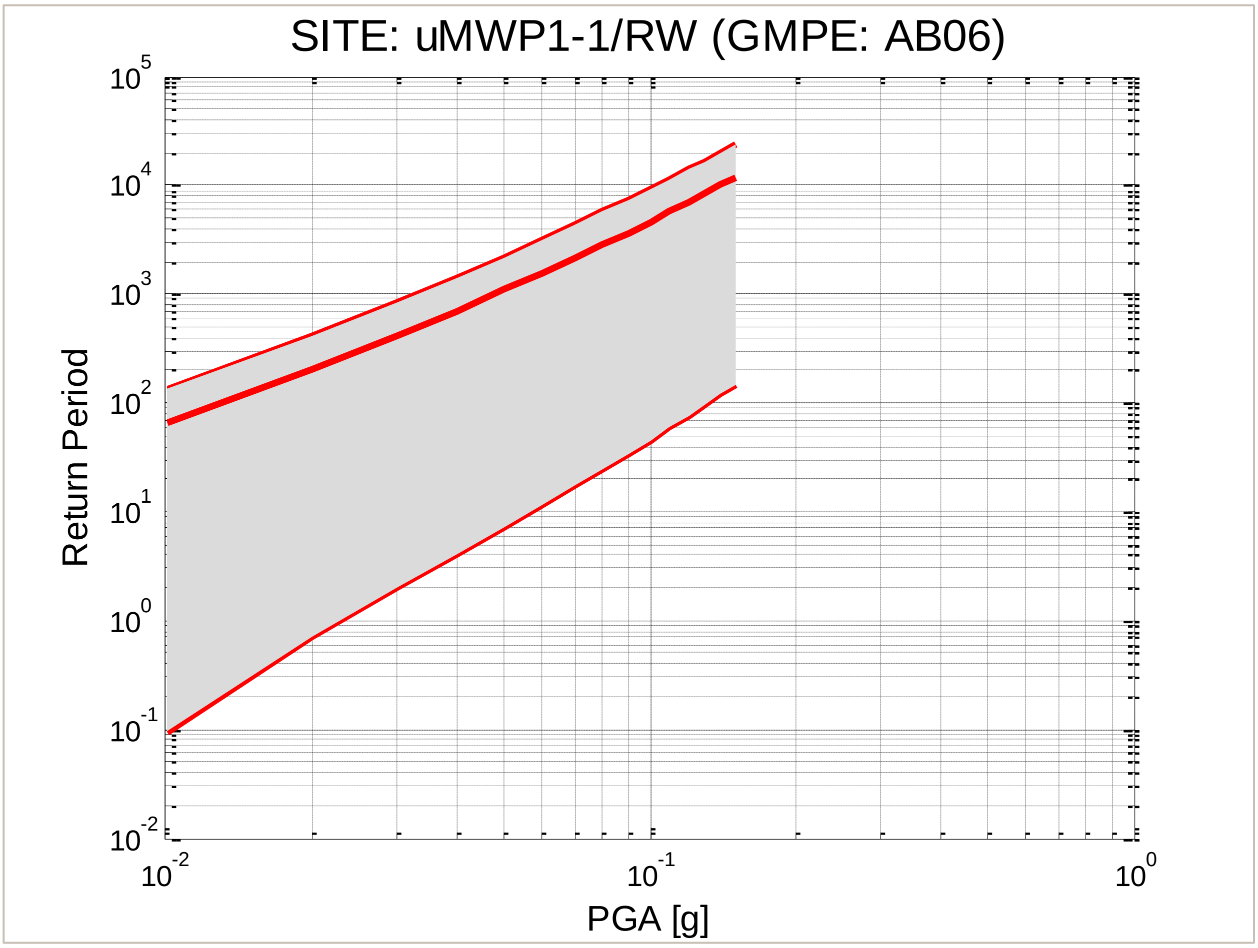

Figure 2(a) Mean return period and its confidence intervals of median value of horizontal PGA at the site of the dam calculated for the ground motion prediction equation AB06 (Atkinson and Boore, 2006).

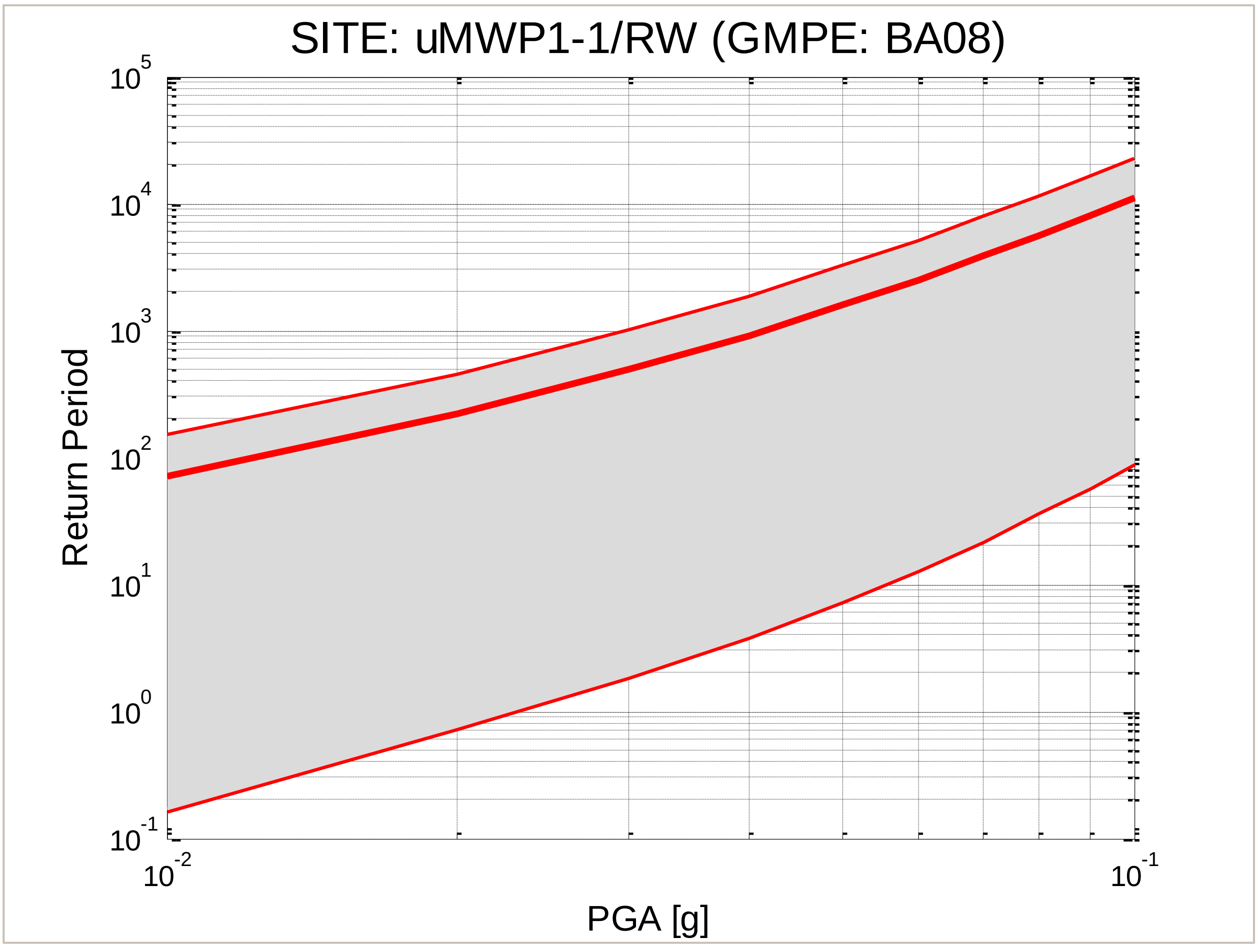

Figure 2(b) Mean return period and its confidence intervals of median value of horizontal PGA at the site of the dam calculated for the ground motion prediction equation BA08 (Boore and Atkinson, 2008).

Appendix G

Attenuation of vertical peak acceleration (by N. A. Abrahamson and J.J. Litehiser)

Attenuation of Vertical Peak Acceleration

N. A. ABRAHAMSON and J. J. LITEHISER

BECHTEL CIVIL, INC., P.O. BOX 3965, SAN FRANCISCO, CALIFORNIA 94119

Peak vertical accelerations from a suite of 585 strong ground motion records from 76 worldwide earthquakes are fit to an attenuation model that has a magnitude dependent shape. The regression uses a two-step procedure that is a hybrid of the Joyner and Boore (1981) and Campbell (1981) regression methods. The resulting vertical attenuation relation is

$$log_{10}a_v(g) = -1.15 + 0.245M - 1.096log_{10}(r + e^{0.256M}) + 0.096F - 0.0011Er, \quad (1)$$

where M is magnitude, r is the distance in kilometers to the closest approach of the zone of energy release, F is a dummy variable that is 1 for reverse or reverse oblique events and 0 otherwise, and E is a dummy variable that is 1 for interplate events and 0 for intraplate events. The standard error of $\log_{10}a_v$ is 0.296.

Because the vertical to horizontal acceleration ratio is also sought, the attenuation of the horizontal peaks from the same suite of records is also obtained using the same regression procedure. The resulting horizontal attenuation relation is

$$log_{10}a_H(g) = -0.62 + 0.177M - 0.982log_{10}(r + e^{0.284M}) + 0.132F - 0.0008Er, \quad (2)$$

where a_H is the peak acceleration of the larger of the two horizontal components. The standard error of $\log_{10}a_H$ is 0.277.

The expected ratio of peak vertical to peak horizontal strong ground motion predicted by these equations (Figure 1) is enveloped by the widely used rule-of-thumb value of two-thirds for earthquakes with magnitudes less than 7.0 and distances greater than 20 km. The expected ratio exceeds 1.0 for earthquakes with magnitudes greater than 8.0 at very short distances. The standard error of $\log_{10}(V/H)$ is 0.20, which is less than the standard error of either the vertical or horizontal acceleration. Therefore, the peak vertical and horizontal accelerations for a given record are strongly correlated and we can have more confidence in the predicted ratio than in either the predicted vertical or horizontal peaks.

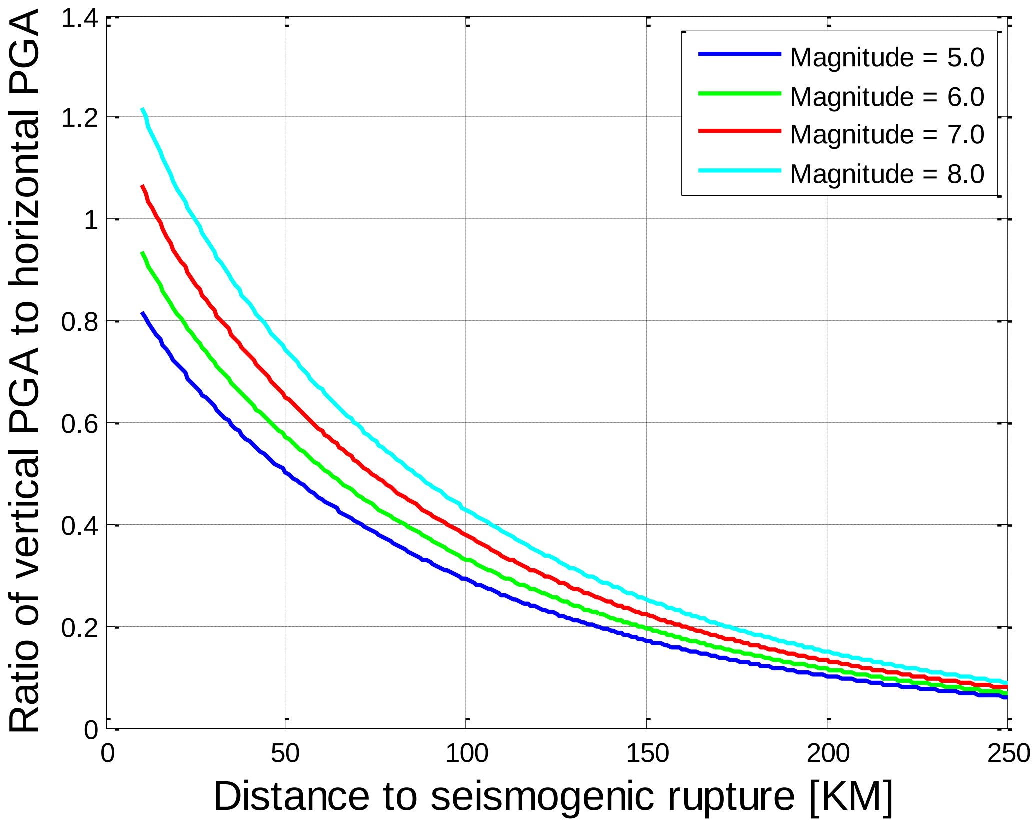

Figure 1 The expected ratio of peak vertical to peak horizontal ground acceleration predicted by equation (1) and (2).

Appendix H

Account of site effect in terms of PGA

Account of Site Effect in Terms of PGA

Any ground motion prediction equation (GMPE) is specific to a soil or rock type on which the PSHA is to be made. These ground types are known as the site classes (International Building Code, 2000; *NEHRP Provisions*, 2001, Table 1), and are classify as hard rock, soft rock, firm soil and soft soil. The site classes are defended by their shear velocities (see table below). The knowledge of the site class is important, since soil have a tendency to amplify long period ground motion vibration and de-amplify short period ground motion.

Table 1. *NEHRP Site Classes. Site class definitions are published in 2000 International Building Code, International Code Council, Inc. on page 350, Table 1615 1.1 Site Class Definitions.*

Site Class	**Soil Profile Name**	**Average Properties in Top 100 feet (as per 2000 IBC section 1615.1.5) Soil Shear Wave Velocity, V_s**	
		Feet/second	Meters/second
A	Hard Rock	$V_{s30} > 5000$	$V_{s30} > 1524$
B	Rock	$2500 < V_s \leq 5000$	$762 < V_s \leq 1524$
C	Very dense soil and soft rock	$1200 < V_s \leq 2500$	$366 < V_s \leq 762$
D	Stiff soil profile	$600 < V_s \leq 1200$	$183 < V_s \leq 366$
E	Soft soil profile	$V_s < 600$	$V_s < 183$
F	Soil requiring site specific evaluations • Soils vulnerable to potential failure or collapse under seismic loading, e.g. liquefiable soils, quick and highly sensitive clays,		

collapsible weakly cemented soils.
- Peats and/or highly organic clays.
- Very high plasticity clays.
- Very thick soft/medium stiff clays – 36 m or thicker layer

Following Atkinson and Boore (2006), the site correction of $\log_{10}$(PGA)**,** denoted as $\Delta\log_{10}(\mathrm{PGA})$ **,** has two components, linear and nonlinear. For PGA ≤ 60 cm/sec^2

$$\Delta\log_{10}(\mathrm{PGA}) = \log_{10}\{\exp[b_{\mathrm{LIN}} \cdot \ln\left(\frac{\mathrm{V_{30}}}{\mathrm{V_{REF}}}\right) + b_{\mathrm{NL}} \cdot \ln\left(\frac{60}{100}\right)]\}. \quad (1)$$

For PGA > 60 cm/sec^2, the same correction is of the form

$$\Delta\log_{10}(\mathrm{PGA}) = \log_{10}\{\exp[b_{\mathrm{LIN}} \cdot \ln\left(\frac{\mathrm{V_{S30}}}{\mathrm{V_{REF}}}\right) + b_{\mathrm{NL}} \cdot \ln\left(\frac{\mathrm{PGA}}{100}\right)]\}. \quad (1)$$

In equation (1) and (2) the PGA is expressed in units of cm/sec^2 and denotes PGA predicted for $\mathrm{V_{S30}}$ = 760 m/sec, or equivalently relative to the reference condition of NEHRP B/C boundary, with $\mathrm{V_{REF}}$ = 760 m/sec. The nonlinear component of the PGA site correction is controlled by parameter b_{NL} and is defined by the following relation

$$b_{\mathrm{NL}} = b_1, \qquad \text{for } V_{S30} \le V_1$$

$$b_{\mathrm{NL}} = (b_1 - b_2)\frac{\ln\left(\frac{V_{s30}}{V_2}\right)}{\ln\left(\frac{V_1}{V_2}\right)}, \qquad \text{for } V_1 < V_{S30} \le V_2$$

$$b_{\mathrm{NL}} = \frac{b_2 \ln\left(\frac{V_{S30}}{V_{\mathrm{REF}}}\right)}{\ln\left(\frac{V_2}{V_{\mathrm{REF}}}\right)}, \qquad \text{for } V_2 < V_{S30} \le V_{\mathrm{REF}}$$

$$b_{\mathrm{NL}} = 0.0, \qquad \text{for } V_{S30} > V_{\mathrm{REF}}.$$

where b_{LIN} = -0.361, V_1 = -0.641 and V_2 = -0.144. The geological materials associated with different values of Vs_{30} are given in Table 2.

Table 2. *Modified NEHRP site classes, associated* Vs_{30} *values and general groupings of geologic units associated with each class (Wills et al., 2000).*

Site Class	**Vs30 (m/s)**	**Geological Materials**
B	> 760	Plutonic/metamorphic rocks incl. most volcanic; pre Tertiary sedimentary units
BC	555-1000	Cretaceous fine - grained sediments ; serpentine ;sheared/weathered crystalline rocks
C	360-760	Oligocene – Cretaceous sedimentary rocks; coarse-grained younger material
CD	270-555	Miocene fine-grained sediments; Plio-Pleistocene alluvium; coarse younger alluvium
D	180-360	Holocene alluvium
DE	90-270	Fine-grained alluvial/estuarine deposits
E	< 180	Inter-tidal mud

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Building Seismic Safety Council (BSSC), 2001. *2000 Edition, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, FEMA-368*, Part 1 (Provisions): Developed for the Federal Emergency Management Agency, Washington, D.C.

Wills, C.J., Petersen, M., Bryant, W.A., Reichle, M., Saucedo, G.J., Tan, S., Taylor, G. and Treiman, J. (2000). A site-condition map for California based on geology and shear-wave velocity. *Bull. Seism. Soc. Am.* **90** (6B), S187-S208.

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Building Seismic Safety Council, 2001, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, 2000 edition, Part 2: Commentary (FEMA 369). Developed for the Federal Emergency Management Agency, Washington, D.C.

Boore, D.M. Joyner, W.B. and Fumal, T.E. (1997). Equations for estimating horizontal response spectra and peak acceleration for Western North American Earthquakes: A summary of recent work. *Seismol. Res. Lett*, **68**, 128-153.

Boore, D.M. (2005). Erratum. Equations for estimating horizontal response spectra and peak acceleration for Western North American Earthquakes: A summary of recent work. *Seismol. Res. Lett*, **76**, 368-369.

Amplification factor for acceleration response spectra

The National Earthquake Hazards Reduction Program (NEHRP) classified the ground to six site classes from A to F. The amplification factor of acceleration response spectrum for each site classes are provided as Table 4.5.1 and Table 4.5.2 (NEHRP Provisions, 2001). The site class B is the rock and the amplification of other site classes were defined comparing to the site class B. The S_s and S_1 in Table 5.5.1 and Table 5.5.2 means the spectral response acceleration value in (g) at 0.2 sec and 1.0 sec of site class B respectively.

Table 4.5.1 Amplification factor for acceleration response spectra at 0.2 sec

Site Class	Mapped Maximum Considered Earthquake Spectral Response Acceleration at Short Periods				
	$S_S \leq 0.25$	$S_S=0.50$	$S_S=0.75$	$S_S=1.00$	$S_S \geq 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	0.9
F	a	a	a	a	a

NOTE: Use straight line interpolation for intermediate values of S_S.
a: Site-specific geotechnical investigation and dynamic site response analyses shall be performed.

Table 4.5.2 Amplification factor for acceleration response spectra at 1.0

Site Class	Mapped Maximum Considered Earthquake Spectral Response Acceleration at 1 Second Periods				
	$S_1 \leq 0.1$	$S_1 = 0.2$	$S_1 = 0.3$	$S_1 = 0.4$	$S_1 \geq 0.5$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4	1.3
D	2.4	2.0	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	2.4
F	a	a	a	a	a

NOTE: Use straight line interpolation for intermediate values of S_1.

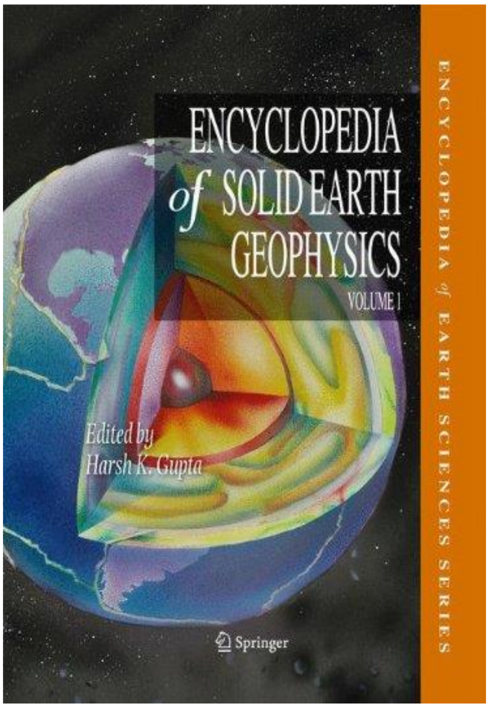
a: Site-specific geotechnical investigation and dynamic site response analyses shall be performed.

Appendix I

"Introduction to Probabilistic Seismic Hazard Analysis" (Extended version of contribution by A. Kijko, Encyclopaedia of Solid Earth Geophysics, Harsh Gupta (Ed.), Springer, 2011

"Introduction to Probabilistic Seismic Hazard Analysis"

Extended version of contribution by A. Kijko to *Encyclopaedia of Solid Earth Geophysics*, Harsh Gupta (Ed.), Springer, 2011.



Seismic Hazard

Encyclopaedia of Solid Earth Geophysics
Harsh Gupta (Ed.)
Springer

Prof Andrzej Kijko Pr. Sci. Nat
University of Pretoria
Room 4-30, Mineral Sciences Building
PRETORIA 0002,
Republic of South Africa
E-mail: andrzej.kijko@up.ac.za
Tel: +27 12 420 3613
Cell: +27 82 939 4002
Fax: +27 12 362 5219

SEISMIC HAZARD

Definition

Seismic hazard. Any physical phenomena associated with an earthquake (e.g., ground motion, ground failure, liquefaction, and tsunami) and their effects on land, man-made structure and socio-economic systems that have the potential to produce a loss. It is also used without regard to a loss to indicate the probable level of ground shaking occurring at a given point within a certain period of time.

Seismic hazard analysis. Quantification of the ground-motion expected at a particular site.

Deterministic seismic hazard analysis. Quantification of a single or relatively small number of individual earthquake scenarios.

Probabilistic seismic hazard analysis. Quantification of the probability that a specified level of ground motion will be exceeded at least once at a site or in a region during a specified exposure time.

Ground motion prediction equation. A mathematical equation which indicates the relative decline of the ground motion parameter as the distance from the earthquake increases.

1. Introduction

The estimation of the expected ground motion which can occur at a particular site is vital to the design of important structures such as nuclear power plants, bridges and dams. The process of evaluating the design parameters of earthquake ground motion is called seismic hazard assessment or seismic hazard analysis. Seismologists and earthquake engineers distinguish between seismic hazard and seismic risk assessments in spite of the fact that in everyday usage these two phrases have the same meaning. Seismic hazard is used to characterize the severity of ground motion at a site regardless of the consequences, while the risk refers exclusively to the consequences to human life and property loss resulting from the occurred hazard. Thus, even a strong earthquake can have little risk potential if it is far from human development and infrastructure, while a small seismic event in an unfortunate location may cause extensive damage and losses.

Seismic hazard analysis can be performed *deterministically*, when a particular earthquake scenario is considered, or *probabilistically*, when likelihood or frequency of specified earthquake size and location are evaluated.

The process of *deterministic* seismic hazard analysis (DSHA) involves the initial assessment of the maximum possible earthquake magnitude for each of the various seismic sources such as active faults or seismic source zones (SSHAC, 1997). An area of up to 450 km radius around the site of interest can be investigated. Assuming that each of these earthquakes will occur at the minimum possible distance from the site, the ground motion is calculated using appropriate attenuation equations. Unfortunately this straightforward and intuitive procedure is overshadowed by the complexity and uncertainty in selecting the appropriate earthquake scenario, creating the need for an alternative, *probabilistic* methodology, which is free from discrete selection of scenario earthquakes. Probabilistic seismic hazard analysis (PSHA) quantifies as a probability whatever hazard may result from all earthquakes of all possible magnitudes and at all significant distances from the site of interest. It does this by taking into account their frequency of occurrence (Gupta, 2002; Thenhaus and Campbell, 2003; McGuire, 2004). Deterministic earthquake scenarios, therefore, are a special case of the probabilistic approach. Depending on the scope of the project, DSHA and PSHA can complement one another to provide additional insights to the seismic hazard (McGuire, 2004). This study will concentrate on a discussion of PSHA.

In principle, any natural hazard caused by seismic activity can be described and quantified by the formalism of the PSHA. Since the damages caused by ground shaking very often result in the largest economic losses, our presentation of the basic concepts of PSHA is illustrated by the quantification of the likelihood of ground-shaking generated by earthquakes. Modification of the presented formalism to quantify any other natural hazard is straightforward.

The classic (Cornell, 1968; Cornell, 1971; Merz and Cornell, 1973; McGuire, 1976) procedure known as Cornell-McGuire procedure for the PSHA includes four steps (Reiter, 1990; Kramer, 1996), (Figure 1).

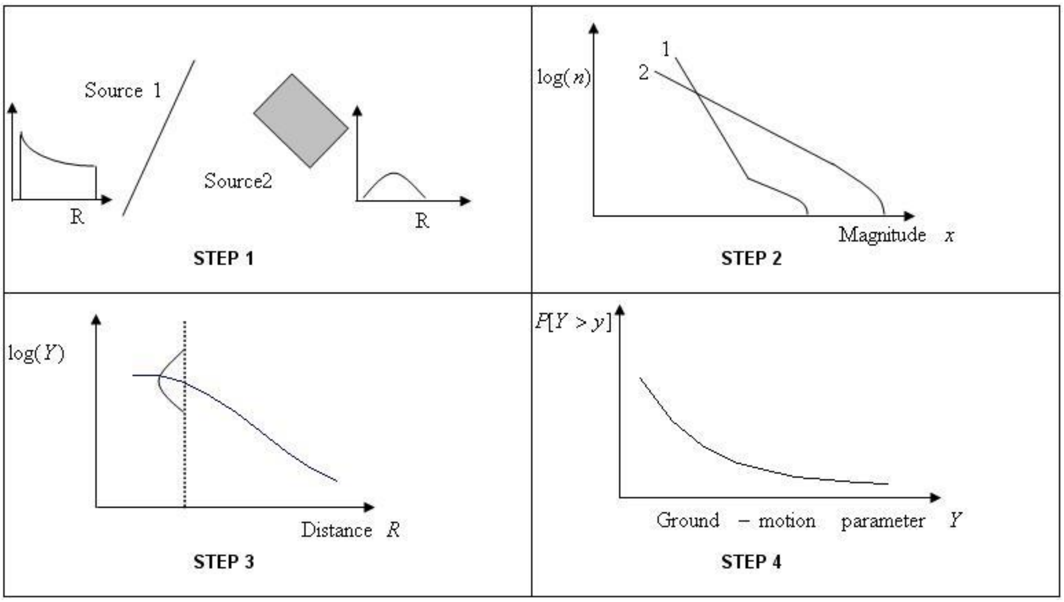


Figure 1. Four steps of a PSHA (modified from Reiter, 1990).

1. The first step of PSHA consists of the identification and parameterization of the *seismic sources* (known also as *source zones*, *earthquake sources* or *seismic zones*) that may affect the site of interest. These may be represented as area, fault, or point sources. Area sources are often used when one cannot identify a specific fault. In classic PSHA, a uniform distribution of seismicity is assigned to each earthquake source, implying that earthquakes are equally likely to occur at any point within the source zone. The combination of earthquake occurrence distributions with the source geometry, results in space, time and magnitude distributions of earthquake occurrences. Seismic source models can be interpreted as a list of potential scenarios, each with an associated magnitude, location and seismic activity rate (Field, 1995).

2. The next step consists of the specification of temporal and magnitude distributions of seismicity for each source. The classic, Cornell-McGuire approach, assumes that earthquake occurrence in time is random and follows the Poisson process. This implies that earthquakes occurrences in time are statistically independent and that they occur at a constant rate. Statistical independence means that occurrence of future earthquakes does not depend on the occurrence of the past earthquake. The most often used model of earthquake magnitude recurrence is the frequency-magnitude Gutenberg-Richter relationship (Gutenberg and Richter, 1944)

$$\log(n) = a - bm, \tag{1}$$

where n is the number of earthquakes with a magnitude of m and a and b are parameters. It is assumed that earthquake magnitude m belongs to the domain $<m_{min}, m_{max}>$, where m_{min} is the level of completeness of earthquake catalogue and magnitude m_{max} is the upper limit of earthquake magnitude for a given seismic source. The parameter a, is the measure of the level of seismicity, while b describes the ratio between the number of small and large events. The Gutenberg-Richter relationship may be interpreted either as being a cumulative relationship, if n is the number of events with magnitude equal or larger than m, or as being a density law, stating that n is the number of earthquakes in a specific, small magnitude interval around m. Under the above assumptions, the seismicity of each seismic source is described by four parameters: the (annual) rate of seismicity λ, which is equal to the parameter of the Poisson distribution, the lower and upper limits of earthquake magnitude m_{min} and m_{max} and the *b*-value of the Gutenberg-Richter relationship.

3. Calculation of ground motion prediction equations and their uncertainty. Ground motion prediction equations are used to predict ground motion at the site itself. The parameters of interest include peak ground acceleration, peak ground velocity, peak ground displacement, spectral acceleration, intensity, strong ground motion duration, etc. Most ground motion prediction equations available today are empirical and depend on the earthquake magnitude, source-to-site distance, type of faulting and local site conditions (Thenhaus and Campbell, 2003; Campbell, 2003; Douglas, 2003; 2004). The choice of an appropriate ground motion prediction equation is crucial since, very often, it is a major contributor to uncertainty in the estimated PSHA.

4. Integration of uncertainties in earthquake location, earthquake magnitude and ground motion prediction equation into probability that the ground motion parameter of interest will be exceeded at the specified site during the specified time interval. The ultimate result of a PSHA is a *seismic hazard curve*: the annual probability of exceeding a specified ground motion parameter at least once. An alternative definition of the hazard curve is the frequency of exceedance *vs* ground motion amplitude (McGuire, 2004).

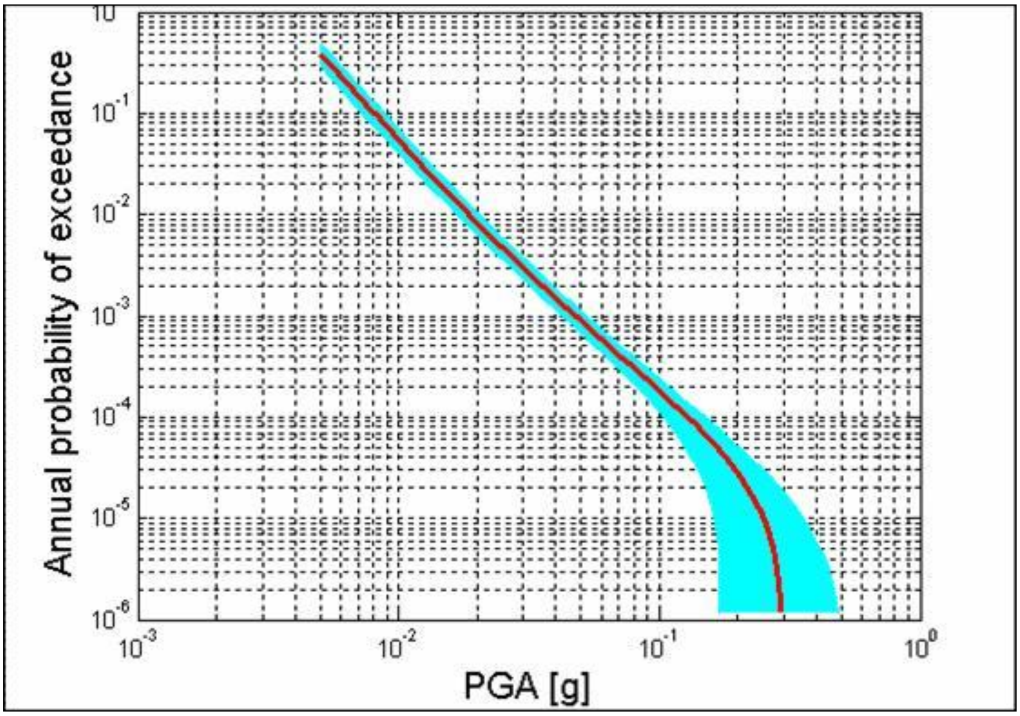


Figure 2. Example of a peak ground acceleration (PGA) seismic hazard curve and its confidence intervals

The following section provides the mathematical framework of the classic PSHA procedure, including its deaggregation. The most common modifications of the procedure will be discussed in the Section 3.

2. The Cornell-McGuire PSHA Methodology

Conceptually, the computation of a seismic hazard curve is fairly simple (Kramer, 1996). Let us assume that seismic hazard is characterized by ground motion parameter *Y*. The probability of exceeding a specified value *y*, $P[Y \geq y]$, is calculated for an earthquake of particular magnitude located at a possible source, and then multiplied by the probability that that particular earthquake will occur. The computations are repeated and summed for the whole range of possible magnitudes and earthquake locations. The resulting probability $P[Y \geq y]$ is calculated by utilizing the Total Probability Theorem (Benjamin and Cornell, 1970) which is:

$$P[Y \geq y] = \sum P[Y \geq y \mid E_i] \cdot P[E_i], \tag{2}$$

where

$$P[Y \geq y \mid E_i] = \int \cdots \int P[Y \geq y \mid x_1, x_2, x_3 ...] \cdot \\ f_i(x_1) \cdot f_i(x_2 \mid x_1) \cdot f_i(x_3 \mid x_1, x_2) \ ... \ dx_3 \, dx_2 \, dx_1. \tag{3}$$

$P[Y \geq y \mid E_i]$ denotes the probability of ground motion parameter $Y \geq y$, at the site of interest, when an earthquake occurs within the seismic source *i*. Variables $x_i \ (i = 1, 2, ...)$ are uncertainty parameters that influence *Y*. In the classic approach, as developed by Cornell (1968), and later extended to accommodate ground motion uncertainty (Cornell, 1971), the parameters of ground motion are earthquake magnitude *M* and earthquake distance *R*. Functions $f(\cdot)$ are probability density functions (PDF) of parameters x_i. Assuming that indeed $x_1 \equiv M$ and $x_2 \equiv R$, $x_2 \equiv R$, the probability of exceedance (3) takes the form:

$$P[Y \geq y \mid E] = \int_{m_{\min}}^{m_{\max}} \int_{R|M} P[Y \geq y \mid m, r] \, f_M(m) \, f_{R|M}(r \mid m) \, dr \, dm, \tag{4}$$

where $P[Y \geq y \mid m, r]$ denotes the conditional probability that the chosen ground motion level *y* is exceeded for a given magnitude and distance; $f_M(m)$ is the probability density function (PDF) of earthquake magnitude, and $f_{R|M}(r \mid m)$ is the conditional PDF of the distance from the earthquake for a given magnitude. The conditional PDF of the distance $f_{R|M}(r \mid m)$ arises in specific instances, such as those where a seismic source is represented by a fault rupture. Since the earthquake magnitude depends on the length of fault rupture, the distance to the rupture and resulting magnitude are correlated.

If, in the vicinity of the site of interest, one can distinguish n_S seismic sources, each with annual average rate of earthquake magnitudes λ_i, then the total average annual rate of events with a site ground motion level *y* or more, takes the form:

$$\lambda(y) = \sum_{i=1}^{n_S} \lambda \int_{m_{\min}}^{m_{\max}} \int_{R|M} P[Y \geq y \mid M, R] \, f_M(m) \, f_{R|M}(r \mid m) \, dr \, dm, \tag{5}$$

In equation (5) the subscripts denoting seismic source number are deleted for simplicity, $P[Y \geq y \mid m, r]$ denotes the conditional probability that the chosen ground motion level *y*, is exceeded for a given magnitude *m* and distance *r*. The standard choice for the probability $P[Y \geq y \mid m, r]$ is a normal, complementary cumulative distribution function (CDF), which is based on the assumption that the ground motion parameter *y* is a log-normal random variable, $\ln(y) = g(m, r) + \varepsilon$, where ε is random error. The mean value of $\ln(y)$ and its standard deviation are known and are defined as $\overline{\ln(y)}$ and $\sigma_{\ln(y)}$ respectively. The function $f_M(m)$ denotes the PDF of earthquake magnitude. In most engineering applications of PSHA, it is assumed that earthquake magnitudes follow the

Gutenberg-Richter relation (1), which implies that $f_M(m)$ is a negative, exponential distribution, shifted from zero to $m_{\min}$ and truncated from the top by $m_{\max}$, (Page, 1968)

$$f_M(m) = \frac{\beta \exp[(-(m - m_{\min})]}{1 - \exp[(-\beta(m_{\max} - m_{\min})]}, \qquad (6)$$

In equation (6), $\beta = b$ ln10, where b is the parameter of the frequency-magnitude Gutenberg-Richter relation (1).

After assuming that in every seismic source, earthquake occurrences in time follow a Poissonian distribution, the probability that y, a specified level of ground motion at a given site, will be exceeded at least once within any time interval t is

$$P[Y > y;\, t] = 1 - \exp[-\lambda(y) \cdot t]. \qquad (7)$$

The equation (7) is fundamental to PSHA. For t=1 year, its plot *vs.* ground motion parameter y, is the *hazard curve* – the ultimate product of the PSHA, (Figure 2). For small probabilities, less than 0.05,

$$P[Y > y;\, t = 1] = 1 - \exp(-\lambda) \cong 1 - (1 - \lambda + \frac{1}{2}\lambda^2 - ...) \cong \lambda\,, \qquad (8)$$

which means that the probability (7) is approximately equal to $\lambda(y)$.

This proves that PSHA can be characterised interchangeably by the annual probability (7) or by the rate of seismicity (5).

In the classic Cornell-McGuire procedure for PSHA it is assumed that the earthquakes in the catalogue are independent events. The presence of clusters of seismicity, multiple events occurring in a short period of time or presence of foreshocks and aftershocks violates this assumption. Therefore, before computation of PSHA, these dependent events must be removed from the catalogue. Most of the procedures used for removal of dependent events are based on empirical, space-time-magnitude distributions (see, e.g., Molchan and Dmitrieva, 1992).

2.1. Estimation of seismic source parameters

Following the classic Cornell-McGuire PSHA procedure, each seismic source is characterised by four parameters:

- level of completeness of the seismic data, $m_{\min}$
- annual rate of seismic activity λ, corresponding to magnitude $m_{\min}$
- b-value of the frequency-magnitude Gutenberg-Richter relation (1)
- upper limit of earthquake magnitude $m_{\max}$

Estimation of $m_{\min}$. The level of completeness of the seismic event catalogue, $m_{\min}$, can be estimated in at least two different ways (Schorlemmer and Woessner, 2008).

The first approach is based on information provided by the seismic event catalogue itself, where $m_{\min}$ is defined as the deviation point from an empirical or assumed earthquake magnitude distribution model. In most cases the model is based on the Gutenberg-Richter relation (1). Probably the first procedure belonging to this category was proposed by Stepp (1973). More recent procedures of the same category are developed e.g. by Weimer and Wyss (2000) and Amorese (2007). Occasionally, $m_{\min}$ is estimated from comparison of the day-to-night ratio of events (Rydelek and Sacks, 1989). Despite the fact that the evaluation of $m_{\min}$ based on information provided entirely by seismic event catalogue is widely used, it has several weak points. By definition, the estimated levels of $m_{\min}$ represent only the average values over space and time. However, most procedures in this category require assumptions on a model of earthquake occurrence, such as a Poissonian distribution in time and frequency-magnitude Gutenberg-Richter relation.

The second approach used for the estimation of m_{min} level is based on a different principle: it utilizes information on the detection capabilities and signal-to-noise ratio of the seismic stations recording the seismic events. The most recently developed techniques that belong to this category have been proposed by Albarello *et al.*, (2001) and Schorlemmer and Woessner (2008). These procedures release users from the assumptions of stationarity and statistical independence of event occurrence. The choice of the most appropriate procedure for m_{min} estimation depends on several factors, such as the knowledge of the history of the development of the seismic network, data collection and processing.

Estimation of rate of seismic activity λ and *b*-value of Gutenberg-Richter. The accepted approach to estimating seismic source recurrence parameters λ and *b* is the maximum likelihood procedure (Weichert, 1980; Kijko and Sellevoll, 1989; McGuire 2004). If successive earthquakes are independent in time, the number of earthquakes with magnitude equal to or exceeding a level of completeness, $m_{min,}$ follows the Poisson distribution with the parameter equal to the annual rate of seismic activity λ . The maximum likelihood estimator of λ is then equal to *n/t*, where *n* is number of events that occurred within time interval *t* (Benjamin and Cornell, 1970).

For given m_{max}, the maximum likelihood estimator of the *b*-value of the Gutenberg-Richter equation can be obtained from the recursive solution of the following:

$$1/\beta = \overline{m} - m_{min} + \frac{(m_{max} - m_{min}) \cdot \exp[-\beta(m_{max} - m_{min})]}{1 - \exp[-\beta(m_{max} - m_{min})]}. \qquad (9)$$

Where $\beta = b \ln 10$, and $\overline{m}$ is the sample mean of earthquake magnitude (Page, 1968). If the range of earthquake magnitudes $< m_{max}, m_{min} >$ exceeds 2 magnitude units, the solution of equation (9) can be approximated by the well known Aki-Utsu estimator (Aki, 1965; Utsu, 1965)

$$\beta = 1 / (\overline{m} - m_{min}). \qquad (10)$$

In most real cases, estimation of parameters λ and the *b*-value by the above simple formulas cannot be performed due to the incompleteness of seismic event catalogues. The typical seismic event catalogue can be divided into two parts. The first part contains only the largest historic events which occurred over a period of a few hundred years while the second part contains instrumental data for a relatively short period of time (in most cases ca. the last 50 years), with varying periods of completeness (Figure 3).

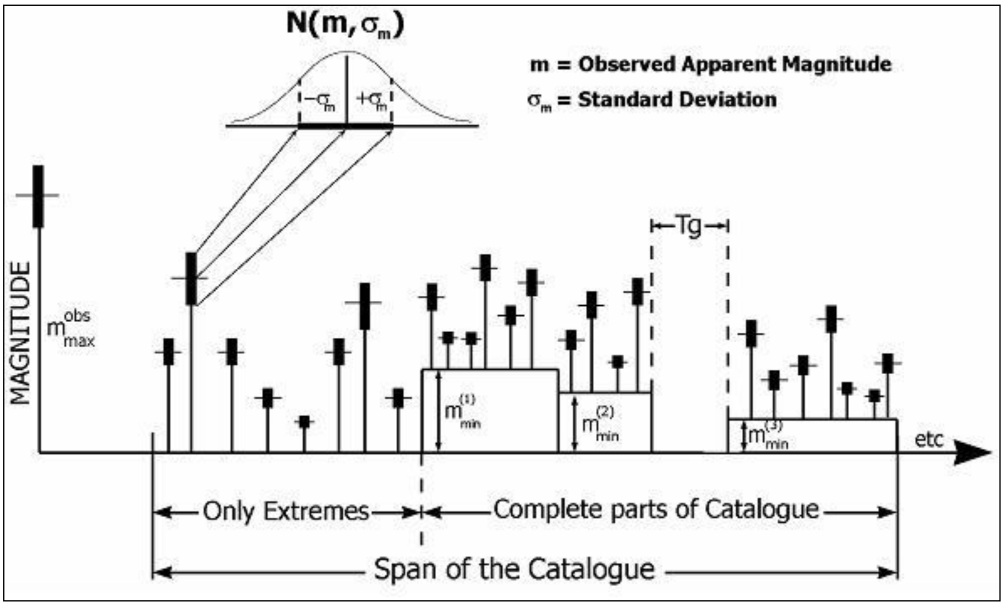


Figure 3. Illustration of data which can be used to obtain maximum likelihood estimators of recurrence oparameters by the procedure developed by Kijko and Sellevoll (1992). The approach permits the combination of largest earthquake data and complete data having variable periods of completeness. It allows the use of the largest known historical earthquake magnitude ($m_{\max}^{obs}$) which occurred before the catalogue began. It also accepts "gaps" (T_g) when records were missing or the seismic networks were out of operation. Uncertainty in earthquake magnitude is taken into account in that an assumption is made that the observed magnitude is true magnitude subjected to a random error that follows a Gaussian distribution having zero mean and a known standard deviation.

The best procedure to utilize all the information contained in the catalogue will combine the macroseismic part of the catalogue (strong events only) with variable periods of completeness. Such a procedure has been developed by Kijko and Sellevoll (1989; 1992). This methodology follows from the similar approach developed by Weichert (1980) which did not accommodate the presence of the macroseismic part of the catalogue, and did not assess the maximum possible earthquake magnitude $m_{\max}$. Comparison of both approaches for catalogues of variable periods of completeness shows that for values of $m_{\max}$ large enough, the two procedures are equivalent (Weichert and Kijko, 1989).

Estimation of $m_{\max}$. The maximum magnitude, $m_{\max}$, is defined as the upper limit of magnitude for a given seismic source. Also, synonymous with the upper limit of earthquake magnitude, is the magnitude of the largest possible earthquake or maximum credible earthquake. This definition of maximum magnitude is also used by earthquake engineers (EERI Committee, 1984), and complies with the meaning of this parameter as used by e.g. the Working Group on California Earthquake Probabilities (WGCEP, 1995; 2008), Stein and Hanks (1998), and Field *et al*. (1999).

This terminology assumes a sharp cut-off magnitude at a maximum magnitude $m_{\max}$. Cognisance should be taken of the fact that an alternative, "soft" cut-off maximum earthquake magnitude is also being used (Main and Burton, 1984; Kagan, 1991). The later formalism is based on the assumption that seismic moments of seismic events follow the Gamma distribution. One of the distribution parameters is called the maximum seismic moment and the corresponding value of earthquake magnitude is called the "soft" maximum magnitude. Beyond the value of this maximum magnitude, the distribution decays much faster than the classical Gutenberg-Richter relation. However, this means that earthquakes with magnitudes larger than such a "soft" maximum magnitude are not excluded. Although this model has been used by Kagan (1994, 1997), Main (1996), Main *et al.* (1999),Sornette and Sornette (1999), the classic PSHA only considers models having a sharp cut-off of earthquake magnitude.

As a rule, $m_{\max}$ plays an important role in PSHA, especially in assessment of long return periods. At present, there is no generally accepted method for estimating $m_{\max}$. It is estimated by the combination of several factors, which are based on two kinds of information (Wheeler, 2009): seismicity of the area, and geological, geophysical and structural information of the seismic source. The utilization of the seismological information focuses on the maximum observed earthquake magnitude within a seismic source and statistical analysis of the available seismic event catalogue. The geological information is used to identify distinctive tectonic features, which control the value of $m_{\max}$.

The current evaluations of $m_{\max}$ are divided between deterministic and probabilistic procedures, based on the nature of the tools applied (e.g. Gupta, 2002).

Deterministic procedures. The deterministic procedure most often applied is based on the empirical relationships between magnitude and various tectonic and fault parameters, such as fault length or rupture dimension. The relationships are different for different seismic areas and different types of faults (Wells and Coppersmith, 1994; Anderson *et al.,* 1996; 2000 and references therein). Despite the fact that empirical relationships between magnitudes and fault parameters are extensively used in PSHA (especially for the assessment of maximum possible magnitude generated by the fault-type seismic sources), the weak point of the approach is its requirement to specify the highly uncertain length of the future rupture. An alternative approach to the determination of earthquake recurrence on singular faults with a segment specific slip rate is provided by the so-called cascade model, where segment rupture is defined by the individual cascade-characteristic rupture dimension (Cramer *et al*., 2000).

Another deterministic procedure which has a strong, intuitive appeal is based on records of the largest historic or paleo-earthquakes (McCalpin, 1996). This approach is especially applicable in the areas of low seismicity, where large events have long return periods. In the absence of any additional tectono-geological indications, it is assumed that the maximum possible earthquake magnitude is equal to the largest magnitude observed, $m_{\max}^{obs}$, or the largest observed plus an increment. Typically, the increment varies from ¼ to 1 magnitude unit. The procedure is often used for the areas with several, small seismic sources, each having its own $m_{\max}^{obs}$ (Wheeler, 2009).

Another commonly used deterministic procedure for $m_{\max}$ evaluation, especially for area-type seismic sources, is based on the extrapolation of the frequency-magnitude Gutenberg-Richter relation. The best known extrapolation procedures are probably those by Frohlich (1998) and the "probabilistic" extrapolation procedure applied by Nuttli (1981), in which the frequency-magnitude curve is truncated at the specified value of annual probability of exceedance (e.g. 0.001).

An alternative procedure for the estimation of $m_{\max}$ was developed by Jin and Aki (1988), where a remarkably linear relationship was established between the logarithm of coda Q_0 and the largest observed magnitude for earthquakes in China. The authors postulate that if the largest magnitude observed during the last 400 years is the maximum possible magnitude $m_{\max}$, the established relation will give a spatial mapping of $m_{\max}$.

Ward (1997) developed a procedure for the estimation of $m_{\max}$ by simulation of the earthquake rupture process. Ward's computer simulations are impressive; nevertheless, one must realize that all the quantitative assessments are based on the particular rupture model, postulated parameters of the strength and assumed configuration of the faults.

The value of $m_{\max}$ can also be estimated from the tectono-geological features like strain rate or the rate of seismic-moment release (Papastamatiou, 1980; Anderson and Luco, 1983; WGCEP, 1995, 2008; Stein and Hanks, 1998; Field *et al.*, 1999). Similar approaches have also been applied in evaluating the maximum possible magnitude of seismic events induced by mining (e.g. McGarr, 1984). However, in most cases, the uncertainty of $m_{\max}$ as determined by any deterministic procedure is large, often reaching a value of the order of one unit on the Richter scale.

Probabilistic procedures. The first probabilistic procedure for maximum regional magnitude was developed in the late sixties, and is based on the formalism of the extreme values of random variables. A major breakthrough in the seismological applications of extreme-value statistics was made by Epstein and Lomnitz (1966), who proved that the Gumbel I distribution of extremes can be derived directly from the assumptions that seismic events are generated by a Poisson process and that they follow the frequency-magnitude Gutenberg-Richter relation. Statistical tools required for the estimation of the end-point of distribution functions (as e.g. Tate, 1959; Robson and Whitlock, 1964; Cooke, 1979) have only recently been used in the estimation of maximum earthquake magnitude (Dargahi-Noubary, 1983; Gupta and Trifunac, 1988; Gupta and Deshpande 1994; Pisarenko *et al*., 1996; Kijko, 2004 and references therein).

The statistical tools available for the estimation of $m_{\max}$ vary significantly. The selection of the most suitable procedure depends on the assumptions of the statistical distribution model and/or the information available on past seismicity. Some of the procedures can be applied in the extreme cases when no information about the nature of the earthquake magnitude distribution is available. Some of the procedures can also be used when the earthquake catalogue is incomplete, i.e. when only a limited number of the largest magnitudes are known. Two estimators are presented here. Broadly speaking, the first estimator is straightforward and simple in application, while the second one requires more computational effort but provides more accurate results (Kijko and Graham, 1998). It is assumed that both the analytical form and the parameters of the distribution functions of earthquake magnitude are known. This knowledge can be very approximate, but must be available.

Based on the distribution of the largest among n observations (Benjamin and Cornell, 1970), and on the condition that the largest observed magnitude $m_{\max}^{obs}$ is equal to the largest magnitude to be expected, the "simple" estimate of $m_{\max}$ is of the form (Pisarenko *et al.*, 1996)

$$\hat{m}_{\max} = m_{\max}^{obs} + \frac{1}{n\, f_M(m_{\max}^{obs})}, \qquad (11)$$

where $f_M(m_{\max}^{obs})$ is PDF of the earthquake magnitude distribution. If applied to the Gutenberg-Richter recurrence relation with PDF (6), it takes the simple form

$$\hat{m}_{\max} = m_{\max}^{obs} + \frac{1-\exp[-\beta(m_{\max}^{obs} - m_{\min})]}{n\beta\exp[-\beta(m_{\max}^{obs} - m_{\min})]}. \qquad (12)$$

The approximate variance of the estimator (12) is of the form

$$VAR(\hat{m}_{\max}) = \sigma_M^2 + \frac{1}{n^2}\left[\frac{1-\exp[-\beta(m_{\max}^{obs} - m_{\min})]}{\beta\exp[-\beta(m_{\max}^{obs} - m_{\min})]}\right]^2, \qquad (13)$$

where σ_M stands for epistemic uncertainty and denotes the standard error in the determination of the largest observed magnitude $m_{\max}^{obs}$. The second part of the variance represents the aleatory uncertainty of $m_{\max}$.

The second ("advanced") procedure often used for assessment of $m_{\max}$ is based on the formalism derived by Cooke (1979)

$$\hat{m}_{\max} = m_{\max}^{obs} + \int_{m_{\min}}^{m_{\max}^{obs}} [F_M(m)]^n \mathrm{d}m, \qquad (14)$$

where $F_M(m)$ denotes the CDF of random variable *m*. If applied to the frequency-magnitude Gutenberg-Richter relation (1), the respective CDF is (Page, 1968)

$$F_M(m) = \begin{cases} 0, & \text{for } m < m_{\min}, \\ \dfrac{1-\exp[-\beta(m-m_{\min})]}{1-\exp[-\beta(m_{\max}-m_{\min})]}, & \text{for } m_{min} \le m \le m_{\max}, \\ 1, & \text{for } m > m_{\max}, \end{cases} \quad (15)$$

and the $m_{\max}$ estimator (14) takes the form

$$\hat{m}_{\max} = m_{\max}^{obs} + \frac{E_1(n_2)-E_1(n_1)}{\beta\exp(-n_2)} + m_{\min}\exp(-n), \quad (16)$$

where $n_1 = n/\{1-\exp[-\beta(m_{\max}^{obs}-m_{\min})]\}$, $n_2 = n_1\exp[-\beta(m_{\max}^{obs}-m_{\min})]$, and $E_1(\cdot)$ denotes an exponential integral function. The variance of estimator (16) has two components, epistemic and aleatory, and is of the form

$$VAR(\hat{m}_{\max}) = \sigma_M^2 + \left[\frac{E_1(n_2)-E_1(n_1)}{\beta\exp(-n_2)} + m_{\min}\exp(-n)\right]^2, \quad (17)$$

where σ_M denotes standard error in the determination of the largest observed magnitude $m_{\max}^{obs}$.

Both above estimators of $m_{\max}$, by their nature, are very general and have several attractive properties. They are applicable for a very broad range of magnitude distributions. They may also be used when the exact number of earthquakes, *n*, is not known. In this case, the number of earthquakes can be replaced by λt. Such a replacement is equivalent to the assumption that the number of earthquakes occurring in unit time conforms to a Poisson distribution with parameter λ, where *t* is the span of the seismic event catalogue. It is also important to note that both estimators provide a value of $\hat{m}_{\max}$, which is never less than the largest magnitude already observed.

Alternative procedures are discussed by Kijko (2004), which are appropriate for the case when the empirical magnitude distribution deviates from the Gutenberg-Richter relation. These procedures assume no specific form of the magnitude distribution or that only a few of the largest magnitudes are known.

Despite the fact, that statistical procedures based the mathematical formalism of extreme values provide powerful tools for the evaluation of $m_{\max}$, they have one weak point: often available seismic event catalogues are too short and insufficient to provide reliable estimations of $m_{\max}$. Therefore the Bayesian extension of statistical procedures (Cornell, 1994), allowing the inclusion of alternative and independent information such as local geological conditions, tectonic environment, geophysical data, paleo-seismicity, similarity with another seismic area, etc., are able to provide more reliable assessments of $m_{\max}$.

2.2. Numerical computation of PSHA

With the exception of a few special cases (Bender, 1984), the hazard curve (7) cannot be computed analytically. For the most realistic distributions, the integrations can only be evaluated numerically (i.e. Frankel, *et al*., 1996; Kramer, 1996; Wesson and Perkins, 2001). The common practice is to divide the possible ranges of magnitude and distance into n_M and n_R intervals respectively. The average annual rate (4) is then estimated as

$$\lambda(Y > y) \cong \sum_{i=1}^{n_S} \sum_{j=1}^{n_M} \sum_{k=1}^{n_R} \lambda_i P[Y > y \mid m_j, r_k] \, f_{M_j}(m_j) \, f_{R_k}(r_k) \Delta m \Delta r \, , \qquad (18)$$

where $m_j = m_{\min} + (j - 0.5) \cdot (m_{\max} - m_{\min}) / n_M$, $r_k = r_{\min} + (k - 0.5) \cdot (r_{\max} - r_{\min}) / n_R$, $\Delta m = (m_{\max} - m_{\min}) / n_M$, and $\Delta r = (r_{\max} - r_{\min}) / n_R$.

If the procedure is applied to a grid of points, it will result in a map of PSHA, in which the contours of the expected ground motion parameter during the specified time interval can be drawn.

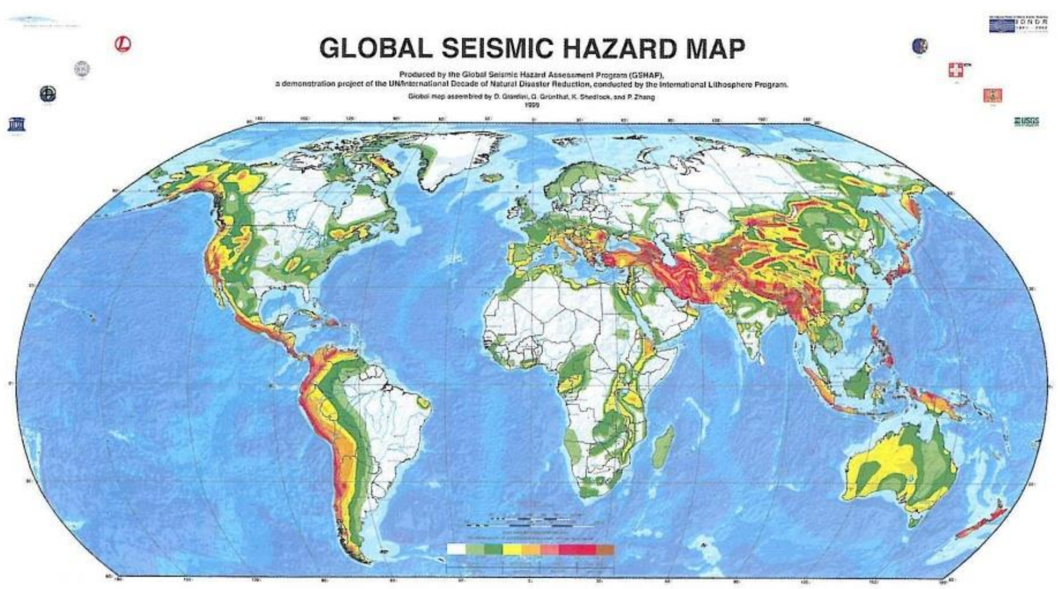


Figure 4. Example of product of PSHA. Map of seismic hazard of the world. Peak ground acceleration expected at 10% probability of exceedance at least once in 50 years. (From Giardini, 1999, http://www.gfz-potsdam.de/pb5/pb53/projects/gshap).

2.3. Deaggregation of Seismic Hazard

By definition, the PSHA aggregates ground motion contributions from earthquake magnitudes and distances of significance to a site of engineering interest. One has to note that the PSHA results are not representative of a single earthquake. However, an integral part of the design procedure of any critical structure is the analysis of the most relevant earthquake acceleration time series, which are generated by earthquakes, at specific magnitudes and distances. Such earthquakes are called "controlling earthquakes" and they are used to determine the shapes of the response spectral acceleration or PGA at the site.

Controlling earthquakes are characterised by mean magnitudes and distances derived from so called deaggregation analysis (e.g. McGuire, 1995; 2004). During the deaggregation procedure, the results of PSHA are separated to determine the dominant magnitudes and the distances that contribute to the hazard curve at a specified (reference) probability. Controlling earthquakes are calculated for different structural frequency vibrations, typically for the fundamental frequency of a structure. In the process of deaggregation, the hazard for a reference probability of exceedance of specified ground motion is portioned into magnitude and distance bins. The relative contribution to the hazard for each bin is calculated. The bins with the largest relative contribution identify those earthquakes that contribute the most to the total seismic hazard.

3. Some Modifications of Cornell-McGuire PSHA Procedure and Alternative Models.

3.1. Source-free PSHA procedures.

The concept of seismic sources is the core element of the Cornell-McGuire PSHA procedure. Unfortunately, seismic sources or specific faults can often not be identified and mapped and the causes of seismicity are not understood. In these cases, the delineation of seismic sources is highly subjective and is a matter of expert opinion. In addition, often, seismicity within the seismic sources is not distributed uniformly, as it is required by the classic Cornell-McGuire procedure. The difficulties experienced in dealing with seismic sources have stimulated the development of an alternative technique to PSHA, which is free from delineation of seismic sources.

One of the first attempts to develop an alternative to the Cornell-McGuire procedure was made by Veneziano *et al*. (1984). Indeed, the procedure does not require the specification of seismic sources, is non-parametric and as input, requires only information about past seismicity. The empirical distribution of the specified seismic hazard parameter is calculated by using the observed earthquake magnitudes, epicentral distances and assumed ground motion prediction equation. By normalizing this distribution for the duration of the seismic event catalogue, one obtains an annual rate of the exceedance for the required hazard parameter.

Another non-parametric PSHA procedure has been developed by Woo (1996). The procedure is also source-free, where seismicity distributions are approximated by data-based kernel functions. Molina *at al*. (2001) compared the Cornell-McGuire and kernel based procedures and found that the former yields a lower hazard. The kernel based approach has also been used by Jackson and Kagan, (1999) where non-parametric earthquake forecasting is achieved by the computation of the annual rate of seismic activity. Again, the procedure is based exclusively on the seismic event catalogue.

By their nature, the non-parametric procedures work well in areas with a frequent occurrence of strong seismic events and where the record of past seismicity is considerably complete. At the same time, the non-parametric approach has significant weak points. Its primary disadvantage is a poor reliability in estimating small probabilities for areas of low seismicity. The procedure is not recommended for an area where the seismic event catalogues are highly incomplete. In addition, in its present form, the procedure is not capable of making use of any additional geophysical or geological information to supplement the pure seismological data. Therefore, a procedure that accommodates the incompleteness of the seismic event catalogues and, at the same time, does not require the specification of seismic sources, would be an ideal tool for analysing and assessing seismic hazard.

Such a procedure, which can be classified as a *parametric-historic* procedure for PSHA (McGuire, 1993), has been successfully used in several parts of the world. Shepherd *et al.* (1993) used it for mapping the seismic hazard in El Salvador. The procedure has been applied in selected parts of the world by the Global Seismic Hazard Assessment Program (GSHAP, Giardini, 1999), while Frankel *et al.* (1996; 2002) applied it for mapping the seismic hazard in the United States. In a series of papers, Frankel and his colleagues modified and substantially extended the original procedure. Their final approach is parametric and based on the assumption that earthquakes within a specified grid size are

Poissonian in time, and that the earthquake magnitudes follow the Gutenberg-Richter relation truncated from the top by maximum possible earthquake magnitude m_{max}.

In some cases, the frequency-magnitude Gutenberg-Richter relation is extended by characteristic events. The procedure accepts the contribution of seismicity from active faults and compensates for incompleteness of seismic event catalogues. The final maps of seismic hazard are smoothed by a Gaussian type kernel function. Frankel's conceptually simple and intuitive parametric-historic approach combines the best of the deductive and non-parametric historic procedures and, in many cases, is free from the disadvantages characteristic of each of the procedures. The rigorous mathematical foundations of the parametric-historic PSHA formalism has been given by Kijko and Graham (1998; 1999) and Kijko (2004).

3.2. Alternative earthquake recurrence models.

Time dependent models. In addition to the classic assumption, that earthquake occurrence in time follows a Poisson process, alternative approaches are occasionally used. These procedures attempt to assess temporal, or temporal and spatial dependence of seismicity. Time dependent earthquake occurrence models specify a distribution of the time to the next earthquake, where this distribution depends on the magnitude of the most recent earthquake. In order to incorporate the memory of past events, the non-Poissonian distributions or Markov chains are applied. In this approach, the seismogenic zones that recently produced strong earthquakes become less hazardous than those that did not rupture in recent history.

Clearly such models may result in a more realistic PSHA, but most of them are still only research tools and have not yet reached the level of development required by routine engineering applications. An excellent review of such procedures is given by Anagnos and Kiremidjian (1988), Cornell and Winterstein (1988), and by Cornell and Toro (1992). Other more recent treatises of the subject are reviewed e.g. by Muir-Wood (1993) and Boschi *et al*. (1996).

Time dependent occurrence of large earthquakes on segments of active faults is extensively discussed by Rhoades *et al.* (1994), Ogata (1999), and recently by Faenza *et al.* (2007). Also, a comprehensive review of all aspects of non-Poissonian models is provided by Kramer (1996). There are several time-dependent models which play an important role in PSHA. The best known models, which have both firm physical and empirical bases, are probably the two models by Shimazaki and Nakata (1980). Based on the correlation of seismic activity with earthquake related coastal uplift in Japan, Shimazaki and Nakata (1980) proposed two models of earthquake occurrence: a *time-predictable* and a *slip-predictable* model.

The time predictable model states that earthquakes occur when accumulated stress on a fault reaches a critical level, however the stress drop and magnitudes of the subsequent earthquakes vary among seismic cycles. Thus, assuming a constant fault-slip rate, the time to the next earthquake can be estimated from the slip of the previous earthquake. The second, the slip-predictable model, is based on the assumption that, irrespective of the initial stress on the fault, an earthquake occurrence always causes a reduction in stress to the same level. Thus, the fault-slip in the next earthquake can be estimated from the time since the previous earthquake (Shimazaki and Nakata, 1980; Scholz, 1990; Thenhaus and Campbell, 2003).

The second group of time-dependent models are less tightly based on the physical considerations of earthquake occurrence, and attempt to describe intervals between the consecutive events by specified statistical distributions. Ogata (1999), after Utsu (1984), considers five models: log-normal, gamma, Weibull, doubly exponential and exponential, which result in the stationary Poisson process. After application of these models to several paleo-earthquake data sets, he concluded that no one of the distributions is consistently the best fit; the quality of the fit strongly depends on the data. From several attempts to describe earthquake time intervals between consecutive events using statistical distributions, at least two play a significant role in the current practice of PSHA: the log-normal model of earthquake occurrence by Nishenko and Buland (1987) and the Brownian passage time (BPT) renewal model by Matthewes *et al*. (2002).

The use of a log-normal model is justified by the discovery that normalized intervals between the consecutive large earthquakes in the circum-Pacific region follow a log-normal distribution with an almost constant standard deviation (Nishenko and Buland, 1987). The finite value for the intrinsic standard deviation is important because it controls the degree of aperiodicity in the occurrence of *characteristic earthquakes*, making accurate earthquake prediction impossible (Scholz, 1990). Since this discovery, the log-normal model has become a key component of most time-dependant PSHA procedures, and is routinely used by the Working Group on California Earthquake Probabilities (WGCEP, 1995).

A time-dependent earthquake occurrence model which is applied more often is the Brownian passage time (BPT) distribution, also known as the inverse Gaussian distribution (Matthewes *et al*., 2002). The model is described by two parameters: μ and σ, which respectively represent the mean time interval between the consecutive earthquakes and the standard deviation. The aperiodicity of earthquake occurrence, as described by the BPT model, is controlled by the variation coefficient $\alpha = \sigma / \mu$. For a small α, the aperiodicity of earthquake occurrence is small and the shape of distribution is almost symmetrical. For a large α, the shape of distribution is similar to log-normal model, i.e. skewed to the right and peaked at a smaller value than the mean. The straightforward control of aperiodicity of earthquake occurrence, by parameter α, makes the BPT model very attractive. It has been used to model earthquake occurrence in many parts of the world and has been applied by the Working Group on California Earthquake Probabilities (1995).

Several comparisons of time-dependent with time-independent earthquake occurrence models (Cornell and Winterstein, 1986, Kramer, 1996; Peruzza *et al.*, 2008) have shown that the time-independent (Poissonian) model can be used for most engineering computations of PSHA. The exception to this rule is when the seismic hazard is dominated by a single seismic source, with a significant component of characteristic occurrence when the time interval from the last earthquake exceeds the mean time interval between consecutive events. Note that, in most cases, the information on strong seismic events provided by current databases is insufficient to distinguish between different models. The use of non-Poissonian models will therefore only be justified if more data will be available.

Alternative frequency-magnitude models. In the classic Cornell-McGuire procedure for PSHA assessment, it is assumed that earthquake magnitudes follows the Gutenberg-Richter relation truncated from the top by a seismic source characteristic, the maximum possible earthquake magnitude m_{max}. The PDF of this distribution is given by equation (5).

Despite the fact that in many cases the Gutenberg-Richter relation describes magnitude distributions within seismic source zones sufficiently well, there are some instances where it does not apply and the relationship (5) must be modified. In many places, especially for areas of seismic belts and large faults, the Gutenberg-Richter relation underestimates the occurrence of large magnitudes. The continuity of the distribution (5) breaks down. The distribution is adequate only for small events up to magnitude 6.0-7.0. Larger events tend to occur within a relatively narrow range of magnitudes (7.5-8.0) but with a frequency higher than that predicted by the Gutenberg-Richter relation (5). These events are known as *characteristic earthquakes* (Youngs and Coppersmith, 1985, Figure 5). Often it is assumed that characteristic events follow a truncated Gaussian magnitude distribution (WGCEP, 1995).

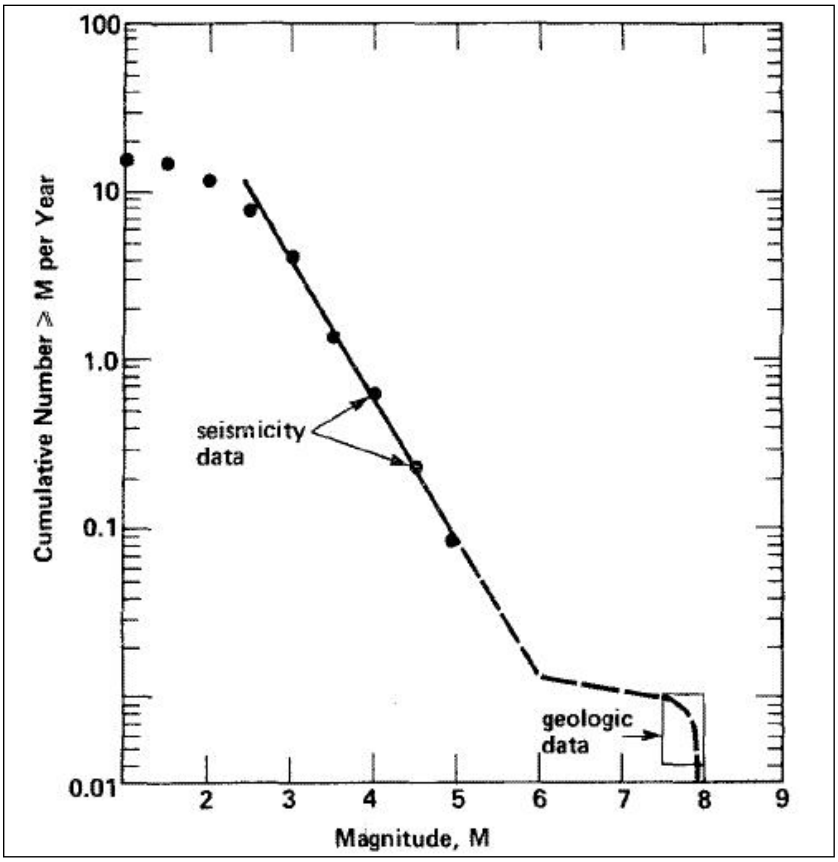


Figure 5. Gutenberg-Richter characteristic earthquake magnitude distribution. The model combines frequency-magnitude Gutenberg-Richter relation a with a uniform distribution of characteristic earthquakes. The model predicts higher rates of exceedance at magnitudes near the characteristic earthquake magnitude. (After Youngs and Coppersmith, 1985).

There are several alternative frequency-magnitude relations, which are used in PSHA. The best known is probably the relation by Merz and Cornell (1973), which accounts for a possible curvature in the log-frequency-magnitude relation (1) by the inclusion of a quadratic term of magnitude. Departure from linearity of the distribution (1) is built into the model by Lomnitz-Adler and Lomnitz (1979). The model is based on simple physical considerations of strain accumulation and release at plate boundaries. Despite the fact that m_{max} is not present in the model, it provides estimates of the occurrence of large events which are more realistic than those predicted by the Gutenberg-Richter relation (1). When seismic hazard is caused by induced seismicity, an alternative distribution to the Gutenberg-Richter model (1) is always required. For example, the magnitude distributions of tremors generated by mining activity are multimodal and change their shape in time (Gibowicz and Kijko, 1994). Often the only possible method that can lead to a successfully PSHA for mining areas is the replacement of the analytical, parametric frequency-magnitude distribution by its model-free, nonparametric counterpart (Kijko *et. al.*, 2001).

Two more modifications of the recurrence models are regularly introduced: one when earthquake magnitudes are uncertain and the other when the seismic occurrence process is composed of temporal trends, cycles, short-term oscillations and pure random fluctuations. The effect of error in earthquake magnitude determination (especially significant for historic events) can be minimized by the simple procedure of correction of the earthquake magnitudes in a catalogue (e.g. Rhoades, 1996). The modelling of random fluctuations in earthquake occurrence is often done by introducing compound distributions in which parameters of earthquake recurrence models are treated as random variables (Campbell, 1982).

4. Ground Motion Prediction Equations

The assessment of seismic hazard at a site requires knowledge of the prediction equation of the particular strong motion parameter, as a function of distance, earthquake magnitude, faulting mechanism and often the local site condition below the site. The most simple and most commonly used form of a prediction equation is

$$\ln(y) = c_1 - c_2 m - c_3 \ln(r) - c_4 r + c_5 F + c_6 S + \varepsilon \,, \tag{19}$$

where y is the amplitude of the ground motion parameter (PGA, MM intensity, seismic record duration, spectral acceleration, etc.); m is the earthquake magnitude, r is the shortest earthquake distance from the site to the earthquake source, F is responsible for the faulting mechanism; S is a term describing the site effect; and ε is the random error with zero mean and standard deviation $\sigma_{\ln(y)}$, which has two components: epistemic and aleatory.

The coefficients $c_1,...,c_6$ are estimated by the least squares or maximum likelihood procedure, using strong motion data. It has been found that the coefficients depend on the tectonic settings of the site. They are different for sites within stable continental regions, active tectonic regions or subduction zone environments (Thenhaus and Campbell, 2003; Campbell, 2003). Assuming that ln(y) has a normal distribution, regression of (19) provides the mean value of ln(y), the exponent of which corresponds to the median value of y, $\breve{y}$, (Benjamin and Cornell, 1970). Since the log-normal distribution is positively skewed, the mean value of y, $\bar{y}$, exceeds the median value $\breve{y}$ by a factor of $\exp(-0.5\sigma^2_{\ln(y)})$. This indicates that the seismic hazard for a particular site is higher when expressed in terms of $\bar{y}$, than the hazard for the same site expressed in terms of $\breve{y}$. It has been shown that the ground motion prediction equation remains a particularly important component of PSHA, since its uncertainty is a major contributor to uncertainty of the PSHA results (Bender, 1984; SSHAC, 1997).

5. Uncertainties in PSHA

Contemporary PSHA distinguishes between two types of uncertainties, aleatory and epistemic.

The *aleatory uncertainty* is due to randomness in nature; it is the probabilistic uncertainty inherent in any random phenomenon. It represents unique details of any earthquake as its source, path, and site and cannot be quantified before the earthquake occurrence and cannot be reduced by current theories, acquiring addition data or information. It is sometimes referred as “randomness”, “stochastic uncertainty” or “inherent variability” (SSHAC, 1997) and is denoted as U_R (McGuire, 2004). The typical examples of aleatory uncertainties are: the number of future earthquakes in a specified area; parameters of future earthquakes such as origin times, epicenter coordinates, depths and their magnitudes; size of the fault rupture; associated stress drop and ground motion parameters like PGA, displacement or seismic record duration at the given site. The aleatory uncertainties are characteristic to the current model and cannot be reduced by the incorporation of addition data. It can only be reduced by the conceptualization of a better model.

The *epistemic uncertainty*, denoted as U_K is the uncertainty due to insufficient knowledge about the model or its parameters. The model (in the broad sense of its meaning; as, e.g., a particular statistical distribution etc.) may be approximate and inexact, and therefore predicts values that differ from the observed values by a fixed, but unknown, amount. If uncertainties are associated with numerical values of the parameters, they are also epistemic by nature. Epistemic uncertainty can be reduced by incorporating additional information or data. Epistemic distributions of a model’s parameters can be updated using the Bayes’ theorem. When new information about parameters is significant and accurate, these epistemic distributions of parameters become delta functions about the exact numerical values of the parameters. In such a case, no epistemic uncertainty about the numerical values of the parameters exists and the only remaining uncertainty in the problem is aleatory uncertainty.

In the past, epistemic uncertainty has been known as statistical or professional uncertainty (McGuire, 2004). The examples of the epistemic uncertainties are: boundaries of seismic sources, distributions of seismic sources parameters (e.g. annual rate of seismic activity λ, *b*-value and m_{max}), or median value of the ground motion parameter given the source properties.

Aleatory uncertainties are included in the PSHA by means of integration over these uncertainties (see eq. 5) and they are represented by the hazard curve. In contrast, epistemic uncertainties are included through the use of an alternative hypothesis - different sets of parameters with different numerical values, different models or through a *logic tree*. Therefore, by default, if in the process of PSHA, the logic tree formalism is applied, the resulting uncertainties of the hazard curve are of epistemic nature.

The major benefit of the separation of uncertainties into aleatory and epistemic is potential guidance in the preparation of input for PSHA and the interpretation of the results. Unfortunately, the division of uncertainties into aleatory and epistemic is model dependent and to a large extent arbitrary, indefinite and confusing (*Panel of Seismic hazard Evaluation* …, 1997; Toro *et al*., 1997; Anderson *et al*., 2000).

6. Logic Tree

The mathematical formalism of PSHA computation, (equation 7 and 9), integrates over all random (aleatory) uncertainties of a particular seismic hazard model. In many cases, however, because of our lack of understanding of the mechanism that controls earthquake generation and wave propagation processes, the best choices for elements of the seismic hazard model is not clear. The uncertainty may originate from the choice of alternative seismic sources, competitive earthquake recurrence models and their parameters as well as from the choice of the most appropriate ground motion. The standard approach for the explicit treatment of alternative hypotheses, models and parameters is the use of a *logic tree* (Coppersmith and Youngs, 1986). The logic tree formalism provides a convenient tool for quantitative treatment of any alternatives. Each node of the logic tree (Figure 6) represents uncertain assumptions, models or parameters and the branches extending from each node are the discrete uncertainty alternatives (McGuire, 2004).

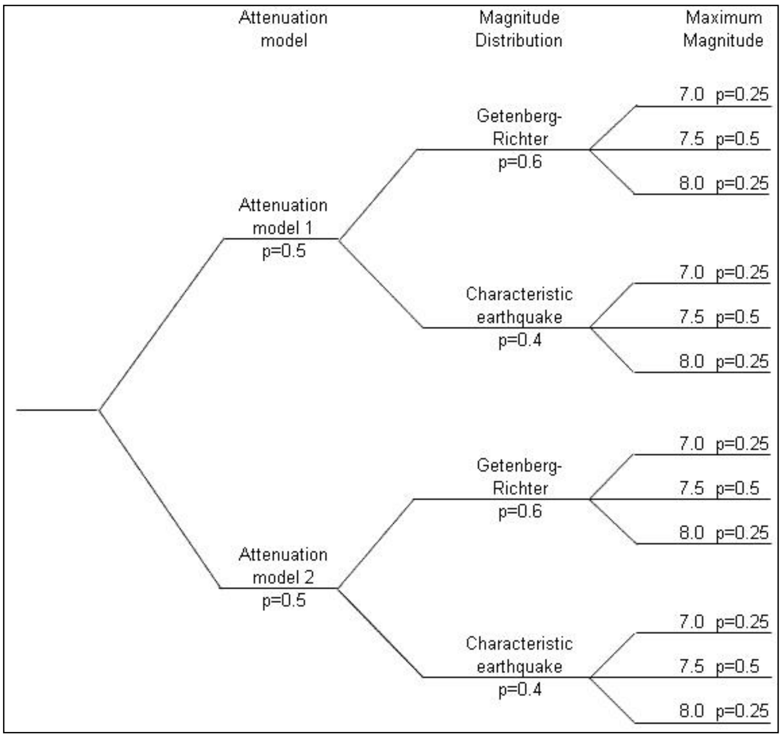


Figure. 6. An example of a simple logic tree. The alternative hypothesis accounts for uncertainty in ground motion attenuation relation, magnitude distribution model and the assigned maximum magnitude m_{max}.

In the logic tree analysis, each branch is weighted according to its probability of being correct. As a result, each end branch represents a hazard curve with an assigned weight, where the sum of weights of all the hazard curves is equal to 1. The derived hazard curves are thus used to compute the final (e.g. mean) hazard curve and their confidence intervals. An example of a logic tree is shown in Figure 6 (Kramer, 1996). The alternative hypotheses account for uncertainty in the ground motion attenuation model, the magnitude distribution model and the assigned maximum magnitude $m_{\max}$.

7. Controversy

Despite the fact that the PSHA procedure, as we know it in its current form, was formulated almost half of century ago, it is not without controversy. The controversy surrounds questions such as: (1) the absence of the upper limit of ground motion parameters, (2) division of uncertainties between aleatory and epistemic, and (3) methodology itself, especially the application of the logic tree formalism.

In most currently used Cornell-McGuire based PSHA procedures, the ground motion parameter used to describe the seismic hazard is distributed log-normally. Since the log-normal distribution is unlimited from the top, it results in a nonzero probability of unrealistically high values for the ground motion parameter, e.g., PGA $\approx$ 20g, obtained originally from a PSHA for a nuclear-waste repository at Yucca Mountain in the USA (Corradini, 2003). The lack of the upper bound of earthquake-generated ground motion in current hazard assessment procedures has been identified as the "missing piece" of the PSHA procedure (Bommer *et al.*, 2004).

Another criticism of the current PSHA procedure concerns portioning of uncertainties into aleatory and epistemic. As noted in Section 5 above, the division between aleatory and epistemic uncertainty remains an open issue.

A different criticism comes from the ergodic assumptions which underlie the formalism of the PSHA procedure. The ergodic process is a random process in which the distribution of a random variable in space is the same as distribution of that variable at a single point, when sampled as a function of time (Anderson and Brune, 1999). It has been shown that the major contribution to PSHA uncertainty comes from uncertainty of the ground motion prediction equation. The uncertainty of the ground motion parameter *y*, is characterised by its standard deviation, $\sigma_{\ln(y)}$, which is calculated as the misfit between the observed and predicted ground motions at several seismic stations for a small number of recorded earthquakes.

Thus, $\sigma_{\ln(y)}$ mainly characterises the spatial and not the temporal uncertainty of ground motion at a single point. This violates the ergodic assumption of the PSHA procedure. According to Anderson and Brune (1999), such violation leads to overestimation of seismic hazard, especially when exposure times are longer than earthquake return times. In addition, Anderson (2000) shows that high-frequency PGA-s observed at short distances do not increase as fast as predicted by most ground motion relations. Therefore the use of the current ground motion prediction equations, especially relating to seismicity recorded at short distances, results in overestimation of the seismic hazard.

A similar view has been expressed by Wang and Zhou (2007) and Wang (2009). *Inter alia* they argue that in the Cornell-McGuire based PSHA procedure, the ground motion variability is not treated correctly. By definition, the ground motion variability is implicitly or explicitly dependent on earthquake magnitude and distance, however, the current PSHA procedure treats it as an independent random variable. The incorrect treatment of ground motion variability results in variability in earthquake magnitudes and distance being counted twice. They conclude that the current PSHA is not consistent with modern earthquake science, is mathematically invalid, can lead to unrealistic hazard estimates and causes confusion. Similar reservations have been expressed in a series of papers by Klügel (see e.g. Klügel, 2007 and references therein)

Equally strong criticism of the currently PSHA procedure has been expressed by Castanos and Lomnitz (2002). The main target of their criticism is the logic tree, the key component of the PSHA. They describe the application of the logic tree formalism as a misunderstanding in probability and statistics, since it is fundamentally wrong to admit "expert opinion as evidence on the same level as hard earthquake data".

The science of seismic hazard assessment is thus subject to much debate, especially in the realms where instrumental records of strong earthquakes are missing. At this time, PSHA represents a best-effort approach by our species to quantify an issue where not enough is known to provide definitive results, and by many estimations a great deal more time and measurement will be needed before these issues can be resolved.

Further reading: There are several excellent studies that describe all aspects of the modern PSHA. Bommer and Abrahamson (2006) and McGuire (2008) trace the intriguing historical development of PSHA. Hanks and Cornell (1999), and Field (1996) present an entertaining and unconventional summary of the issues related to PSHA, including its misinterpretation. Reiter (1990) comprehensively describes both the deterministic as well as probabilistic seismic hazard procedures from several points of view, including a regulatory perspective. Seismic hazard from the geologist's perspective is described in the book by Yeats *et al*., (1997). Kramer (1996) provides an elegant, coherent and understandable description of the mathematical aspects of both, DSHA and PSHA. Anderson *et al*. (2000), Gupta (2002), and Thenhaus and Campbell (2003), present excellent overviews covering theoretical, methodological as well as procedural issues of modern PSHA. Finally, the most comprehensive treatment to date of all aspects of PSHA, including treatment of *aleatory* and *epistemic* uncertainties, is provided by the SSHAC (1997) report and in book form by McGuire (2004). The presentations here benefited from all quoted above sources, especially the excellent book by Kramer (1996).

8. Summary

Seismic hazard is a term referring to any physical phenomena associated with an earthquake (e.g., ground motion, ground failure, liquefaction, and tsunami) and their effects on land, man-made structures and socio-economic systems that have the potential to produce a loss. The term is also used, without regard to a loss, to indicate the probable level of ground shaking occurring at a given point within a certain period of time. Seismic hazard analysis is an expression referring to quantification of the expected ground-motion at the particular site. Seismic hazard analysis can be performed deterministically, when a particular earthquake scenario is considered, or probabilistically, when the likelihood or frequency of a specified level of ground motion at a site during a specified exposure time is evaluated. In principle, any natural hazard caused by seismic activity can be described and quantified in terms of the probabilistic methodology. Classic probabilistic seismic hazard analysis (PSHA) includes four steps: (1) identification and parameterization of the seismic sources, (2) specification of temporal and magnitude distributions of earthquake occurrence, (3) calculation of ground motion prediction equations and their uncertainty, and (4) integration of uncertainties in earthquake location, earthquake magnitude and ground motion prediction equations into the hazard curve.

An integral part of PSHA is the assessment of uncertainties. Contemporary PSHA distinguishes between two types of uncertainties, aleatory and epistemic. The aleatory uncertainty is due to randomness in nature; it is the probabilistic uncertainty inherent in any random phenomenon. The aleatory uncertainties are characteristic to the current model and cannot be reduced by the incorporation of addition data. The epistemic uncertainty is the uncertainty due to insufficient knowledge about the model or its parameters. Epistemic uncertainty can be reduced by incorporating additional information or data. Aleatory uncertainties are included in the probabilistic seismic hazard analysis due to the integration over these uncertainties and they are represented by the hazard curve. In contrast, epistemic uncertainties are included through the use of alternative models, different sets of parameters with different numerical values or through a logic tree.

Unfortunately, the PSHA procedure, as we know it in its current form, is not without controversy. The controversy arises from questions such as: (1) the absence of the upper limit of ground motion parameter, (2) division of uncertainties between aleatory and epistemic, and (3) methodology itself, especially the application of the logic tree formalism

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