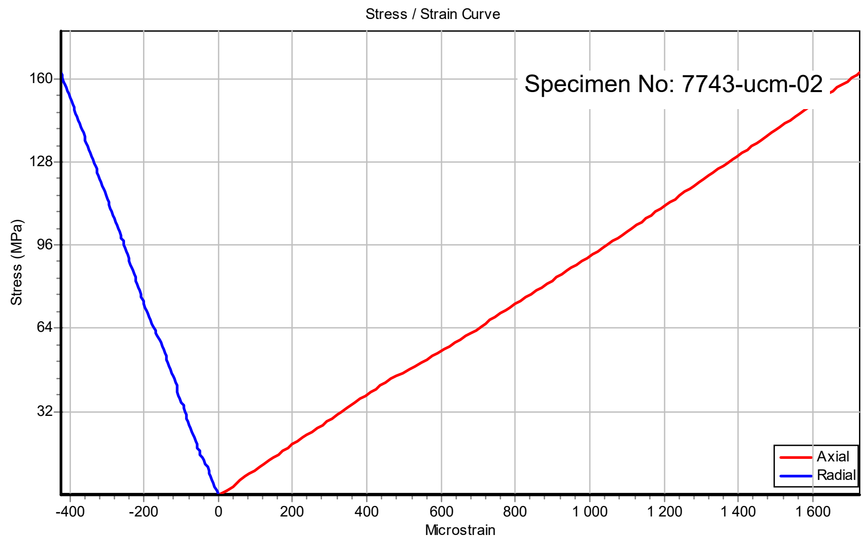
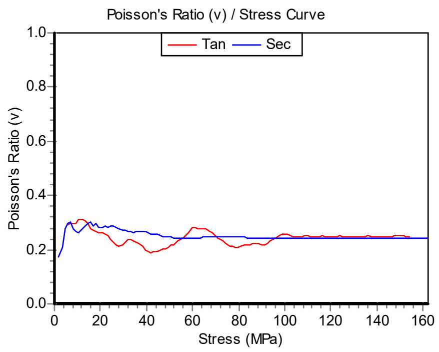
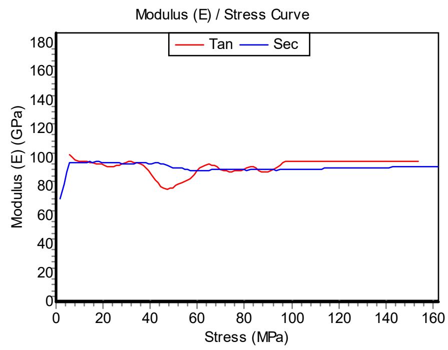
UNIAXIAL COMPRESSION TEST

2018/11/07 10:40:43

WITH ELASTIC MODULUS AND POISSON'S RATIO MEASUREMENTS BY MEANS OF STRAIN GAUGES







Failure Load: 345.5 kN

Peak Strength: 162.3 MPa

Axial Strain at Failure: 1727 microstrain

% Strength	Strength (MPa)	E Tan (GPa)	E Sec (GPa)	v Tan	v Sec
10	16.2	95.9	97.3	0.270	0.289
20	32.5	96.8	96.2	0.240	0.267
30	48.7	79.3	93.4	0.207	0.246
40	64.9	95.3	91.7	0.276	0.247
50	81.2	93.7	91.8	0.219	0.246
60	97.4	97.4	91.8	0.251	0.241
70	114	97.5	92.6	0.250	0.243
80	130	97.5	93.2	0.250	0.244
90	146	97.5	93.6	0.250	0.245

ROCKLAB

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APPENDIX 2

CLASSIFICATION OF ROCK SPECIMEN FAILURE MODE INFLUENCED / NOT INFLUENCED BY DISCONTINUITIES DURING COMPRESSION TESTING

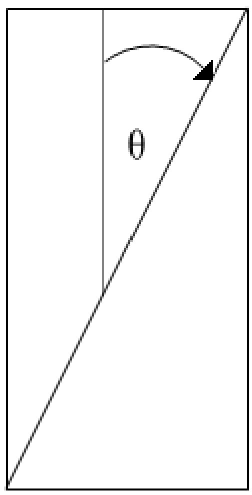
FAILURE NOT INFLUENCED BY DISCONTINUITIES (INTACT)

TYPE CODE	DESCRIPTION OF SUB CODES	
	A	B
X	SINGLE SLIDING SHEAR FAILURE	COMPLETE CONE DEVELOPMENT
Y	SPLITTING	

FAILURE INFLUENCED BY DISCONTINUITIES

TYPE CODE	DESCRIPTION OF SUB CODES	
	A	B
	PARTIAL FAILURE ON DISCONTINUITY	FAILURE COMPLETELY ON DISCONTINUITY
1	AT 0-10° TO AXIS	AT 0-10° TO AXIS
2	AT 11-20° TO AXIS	AT 11-20° TO AXIS
3	AT 21-30° TO AXIS	AT 21-30° TO AXIS
4	AT 31-40° TO AXIS	AT 31-40° TO AXIS
5	AT 41-50° TO AXIS	AT 41-50° TO AXIS
6	AT 51-70° TO AXIS	AT 51-70° TO AXIS
7	AT 71-90° TO AXIS	AT 71-90° TO AXIS
0	Multiple Discontinuities	Multiple Discontinuities

Example: Failure Type3B: Failure completely on a discontinuity with an orientation of between 21°and 30° to the specimen axis.



APPENDIX C

Deterministic Seismic Hazard Analysis Report

DETERMINISTIC SEISMIC HAZARD ANALYSIS

for

Kareerand Tailing Dam, Stilfontein

Submitted to

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Report No: 2016-17/2 (Rev 2.0)

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Appendices

Appendix A: Seismicity of area surrounding the Kareerand Tailing Dam in the radius of 50 km.

Appendix B: Results of seismic hazard analysis for the area in vicinity of the KTD in terms of seismic event magnitude (tabulated values of mean activity rate, return periods and probability of exceedance in 1, 5, 10 and 25 years).

Appendix C: Attenuation of Vertical Peak Acceleration (by N. A. Abrahamson and J.J. Litehiser)

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

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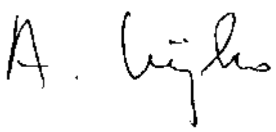

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Prof. A. Kijko 12 November 2017 (Rev 2.0)
NHAC

1. Executive Summary

A Deterministic Seismic Hazard Analysis (DSHA) has been performed for the site of the Kareerand Tailing Dam (KTD), Stilfontein. All known seismic events with magnitude $M_W \geq 3.0$ located within a radius of 50 km from the site were used in the assessment.

The study consists of the development of a particular seismic scenario upon which a seismic hazard evaluation is based (Reiter, 1990; Kramer, 1996). The scenario consists of the postulated occurrence of seismic event of a specified size occurring in a specified area. The DSHA for the KTD includes the following investigations:

- Compilation of a seismic events catalogue and selection of seismic event within a 50 km radius of the dam.

- Identification of seismic event capable of producing significant ground motion (peak ground acceleration) at the site of the dam.

- Assessment of the annual probability of exceeding the specified value of seismic event magnitude and its return period. At the same time the analysis provides assessment of the worst-case scenario, i.e. occurrence of seismic event with the maximum possible magnitude in vicinity of the dam.

- A selection of the controlling seismic event, i.e. the event that is expected to generate the strongest level of shaking, in our case, expressed in terms of PGA. The controlling event is described in terms of its magnitude and distance from the dam site. In this report the controlling event is determined as event of M_W magnitude 5.63$\pm$0.11 located at the epicenter of 9th March 2005 Stilfontein event. The M_W = 5.63$\pm$0.11 is considered as maximum possible, mine related seismic event magnitude, characteristic to the area.

- Selection of most adequate Modified Mercalli intensity (MMI) prediction equation (IPE). All calculations are repeated three times, each for a different IPE:

  (1) *Stable Continental Regions – Modified***.** The IPE was originally designed as intensity prediction equation for stable continental regions and modified for South African conditions (Midzi *et al*., 2015).
  (2) *Regional.* The IPE developed exclusively for the Klerksdorp gold mining area (Hattingh *et al*., 2006).
  (3) *Stable Continental Regions – Global.* The IPE developed for European stable continental region. The IPE provides the lowest residuals for near-source (< 50 km) intensity observations in stable continental regions (Bakun and Scotti, 2006).

- Conversion of estimated MMI into PGA. Since it is unclear which conversion formula of MMI into PGA are best suited for the region, two classic conversion formulas were applied (Ambraseys, 1974, and Trifunac and Brady, 1975) and the final PGA was determined by application of the logic tree formalism.

- The development of a Newmark and Hall Elastic Acceleration Response Spectra for 5% damping anchored at PGA predicted at the dam site by the occurrence of the controlling seismic event.

The results of the DSHA are given in terms of largest expected horizontal value of the peak ground acceleration calculated by application of logic tree formalism.

The predicted largest horizontal PGA at the site of dam is 0.152 ± 0.098 g.

Lists of all seismic events used in the study are given in Appendix A. Appendix B provides results of seismic hazard analysis for area in vicinity of the KTD in terms of seismic event magnitude (tabulated values of mean activity rate, return periods and probability of exceedance in 1, 5, 10 and 25 years). Appendix C provides study by N.A. Abrahamson and J.J. Litehiser on the attenuation of the vertical peak acceleration. Finally, the Appendix D provides the fundamentals of a deterministic and probabilistic seismic hazard analysis.

2. 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 (λ_A)	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 characterising 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 (M_L)	A magnitude scale introduced by Richter (1935) for earthquakes in southern California. M_L 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, M_L 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 (M_L) was originally defined in Richter (1935) as the logarithm of the maximum amplitude in micrometres 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 (m_b), surface-wave magnitude (M_S), and moment magnitude (M_W). 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).
Oscillator	In earthquake engineering, an oscillator is an idealised 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.
IPE	Intensity prediction equation

3. List of Figures and Tables

3.1. List of Figures

3.2. List of Tables

4. Terms of Reference

Due extremely high seismic activity in vicinity of the Kareerand Tailing Storage Facility (9th March 2005, Stilfontein seismic event with magnitude 5.3 and Orkney event 5th, August 2014, magnitude 5.4), the Natural Hazard Assessment Consultancy (NHAC) was requested by Mr Duncan Grant-Stuart, Technical Consultant Knight Piésold (Pty) Ltd (E: dgrant-stuart@knightpiesold.com), to provide desk study of a deterministic seismic hazard analysis (DSHA) for the site of KTD. No geological investigations were required at this stage.

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

1. Those resulting directly from a certain level of ground shaking.

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

This study only covers category one and the case of deterministic seismic hazard analysis (DSHA) and is limited to the following investigations:

- Compilation of a seismic events catalogue within a 50 km radius of the dam.

- Identification of seismic event capable of producing significant ground motion (peak ground acceleration) at the site of the dam.

- Assessment of the annual probability of exceeding the specified value of seismic event magnitude and its return period. At the same time the analysis provides assessment of the worst-case scenario, i.e. occurrence of seismic event with the maximum possible magnitude in vicinity of the dam.

- Assessment of effect of the controlling seismic event, i.e. the event that is expected to generate the strongest level of shaking, in our case, expressed in terms of peak ground acceleration (PGA). The controlling event is described in terms of its magnitude and distance from the dam site.

- Selection of most adequate Modified Mercalli intensity (MMI) prediction equation (IPE).

- Conversion of estimated MMI into PGA.

- The development of a Newmark and Hall Elastic Acceleration Response Spectra for 5% damping anchored at PGA predicted at the dam site by the occurrence of the controlling seismic event.

The results of the DSHA are given in terms of largest expected horizontal peak ground acceleration calculated by application of logic tree formalism.

Lists of all seismic events used in the study are given in Appendix A. Appendix B provides results of seismic hazard analysis for the area in vicinity of KTD in terms of seismic event magnitude (tabulated values of mean activity rate, return periods and probability of exceedance in 1, 5, 10 and 25 years). Appendix C provides work by N.A. Abrahamson and J.J. Litehiser on the attenuation of the vertical peak acceleration. Finally, the Appendix D provides the fundamentals of a deterministic and probabilistic seismic hazard analysis.

5. Deterministic Seismic Hazard Analysis – Fundamentals.

Deterministic seismic hazard analysis (DSHA) involves the development of a particular seismic scenario, according to which expected damages (losses) can be estimated. It provides a framework for evaluation of the worst-case damages. However, it provides no information on the likelihood of occurrence of such damages. Deterministic seismic hazard analysis, involves subjective assumptions, particularly regarding earthquake potential as described by the area characteristic, maximum possible earthquake magnitude $m_{\max}$ (Reiter, 1990).

The earthquake magnitudes referred to are moment, M_W Richter scale magnitudes (Lay and Wallace, 1995). These magnitudes are a measure of the total energy released at the hypocentre of the earthquake with the hypocentre defined as the underground, initial point of origin of an earthquake compared to the epicentre which is the point on the surface of the earth directly above the hypocentre (Lay and Wallace, 1995). The increase of earthquake magnitude by one unit corresponds with the increase in energy released by an earthquake by approximately 30 times. The strength of a seismic event at a given site is measured in terms of the Modified Mercalli intensity (MMI) scale, a subjective scale based on resultant structural damage to buildings. The MMI felt at a specific location varies according to the distance from the hypocentre of the earthquake to the location.

There are two common assumptions made in modelling of seismic event occurrence. Firstly, the number of main seismic events in the time interval T, follows a Poisson distribution with parameter λT, where λ is the frequency (annual mean activity rate) of earthquake occurrence. Secondly, the earthquake magnitudes follow the Gutenberg-Richter relation (Gutenberg and Richter, 1956),

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

where n is the number of earthquakes, m is the earthquake magnitude, a is a constant measuring the level of seismicity and b is a constant which characterises the ratio between small events to large ones. The Gutenberg-Richter relation is the logarithm-frequency-magnitude relation where the plot of the logarithm of the number of earthquakes against the magnitude is linear.

If the magnitudes of seismic events are assumed to be independent, identically distributed random variables, where the frequency-magnitude Gutenberg-Richter relation (1) can be expressed in terms of distribution functions as (Page, 1968)

$$f_M(m) = \begin{cases} 0 & m < m_{\min} \\ \dfrac{\beta \exp[-\beta(m - m_{\min})]}{1 - \exp[-\beta(m_{\max} - m_{\min})]} & m_{\min} \le m \le m_{\max} \\ 0 & m > m_{\max} \end{cases} \tag{2}$$

and

$$F_M(m) = \begin{cases} 0 & m < m_{\min} \\ \dfrac{1 - \exp[-\beta(m - m_{\min})]}{1 - \exp[-\beta(m_{\max} - m_{\min})]} & m_{\min} \le m \le m_{\max}, \\ 1 & m > m_{\max} \end{cases} \quad (3)$$

where $f_M(m)$ and $F_M(m)$ are respectively the probability density function (PDF) and cumulative distribution function (CDF) of magnitude m, where $m_{\min} \le m \le m_{\max}$, $\beta = b\ln(10)$ and b is the b-parameter of the Gutenberg-Richter relation (1). The maximum likelihood estimator of the β -value, denoted as $\hat{\beta}$, can be obtained from solution of equation (Page, 1968)

$$\frac{1}{\beta} = \bar{m} - m_{\min} + \frac{(m_{\max} - m_{\min}) \exp[-\beta(m_{\max} - m_{\min})]}{1 - \exp[-\beta(m_{\max} - m_{\min})]}, \quad (4)$$

where $\bar{m}$ is the sample mean magnitude. The value of $\hat{\beta}$ can be obtained only by recursive solutions. The approximate standard error of $\hat{\beta}$, denoted as $\hat{\sigma}_\beta$, is (Aki, 1965)

$$\hat{\sigma}_\beta = \frac{\hat{\beta}}{\sqrt{n}} \quad (5)$$

such that n is number of earthquakes with magnitudes greater or equal to $m_{\min}$.

It is also assumed that n earthquakes with magnitudes larger or equal to $m_{\min}$ that occurred in a specified time interval T are recorded. The time span T for the seismic event catalogue is measured in years. The earthquake magnitudes are assumed to be random variables with the PDF $f_M(m)$ and CDF $F_M(m)$. The magnitudes are denoted as m_i $(i = 1,2, \ldots, n)$ and ordered such that m_n is the maximum observed earthquake and $m_{\min} \le m_1 \le \cdots \le m_n = m_{\max}^{obs} \le m_{\max}$.

An integral part of any DSHA is the selection of an area-characteristic intensity prediction equation (IPE) and the calculation of the expected ground motion at the site as generated by the control earthquake. An MMI IPE is a relationship that translates the maximum (focal) MMI at the epicentre (I_0) into MMI at the site. The most often used the IPE relation has the following form

$$I_0 - I = -a_1 - a_2 \ln r - a_3 r, \quad (6)$$

where a_1, a_2, a_3 are empirical coefficients, r is the chosen epicentral or hypocentral distance, I is MMI at the site and I_0 is the maximum (focal) MMI at the epicentre. The numerical values of coefficients a_1, a_2, a_3 are different for different regions and are usually estimated from MMI distribution maps of the region. The empirical relation between earthquake magnitude m and MMI at the epicentre I_0, is given by (Richter, 1958):

$$I_0 = \frac{3}{2}m - 1. \tag{7}$$

5.1 Assessment of the Maximum Regional Earthquake magnitude, $m_{\max}$

The maximum possible earthquake magnitude $m_{\max}$ is defined as the upper limit of earthquake magnitude for a given region. Also, synonymous with the upper limit of earthquake magnitude is the magnitude of the largest possible earthquake for a given region (EERI Committee, 1984).

Although value of $m_{\max}$ is one of the most important parameter in seismic hazard analysis, it is astonishing how little has been done in developing appropriate techniques for its estimation. Presently, there is no universally accepted technique for estimating the value of $m_{\max}$, however, the current procedures for $m_{\max}$ can be divided into two main categories: deterministic and probabilistic. A presentation and discussion of deterministic techniques for the assessment of $m_{\max}$ can be found in e.g. Wells and Coppersmith (1994); Wheeler (2009) and Mueller (2010).

The selection of the applied probabilistic procedure depends on the assumptions about the statistical distribution model and/or the information available about past seismicity. Taking into account that in the case of seismic hazard assessment for the KTD, the available data are extremely uncertain, the most appropriate is the nonparametric procedure which is applicable in case of uncertainty of both, the data and the recurrence model (Kijko and Singh, 2011).

Let us assume that the form of the magnitude distribution is not known and we wish to estimate the right end point of the distribution, viz. the maximum earthquake magnitude $m_{\max}$. One of the methods to solve this problem is to apply the classic Quenouille (1956) technique of successive bias reduction, modified to fit the factorial series rather than the power series in $1/n$. Robson and Whitlock (1964) showed that, under very general conditions, and when the data are arranged in ascending order of magnitude, viz. $m_{\min} \le m_1 \le \cdots \le m_n = m_{\max}^{obs}$, Quenouille's approach leads to the following rule in estimation of $m_{\max}$

$$\hat{m}_{\max} = m_{\max}^{obs} + (m_{\max}^{obs} - m_{n-1}) \tag{8}$$

Equation (8) was first derived by Robson and Whitlock (1964), and is often called the Robson and Whitlock (R-W) estimator. It can be shown that the above estimator is mean-unbiased to order n^{-2} and asymptotically median-unbiased.

The simplicity of the (8) makes it very attractive. It can be applied in cases of limited and/or doubtful seismic data, when quick results, without going into sophisticated analysis, is required. Unfortunately, the reduction of bias of the R-W estimator can be achieved only at the expense of a high value of its mean squared error. In fact, Robson and Whitlock (1964) derived a general formula for an unbiased estimator of truncation point,

$$\hat{m}_{\max} = \sum_{j=0}^{k} (-1)^j \binom{k+1}{j+1} m_{n-j} , \tag{9}$$

where $k = 1,\dots, n\text{-}1$. Regrettably, this formula does not provide a guarantee that the estimated magnitude $\hat{m}_{max}$ is equal to, or exceeds, the observed maximum magnitude $\hat{m}_{max}^{obs}$. The approximate variance of the R-W estimator of $m_{\max}$ for the frequency-magnitude Gutenberg-Richter distribution is of the form

$$VAR(\hat{m}_{\max}) = 5\sigma_M^2 + (m_{\max}^{obs} - m_{n-1})^2 , \tag{10}$$

where σ_M denotes standard error in the determination of the two largest observed magnitudes $m_{\max}^{obs}$ and m_{n-1}.

In their seminal work Robson and Whitlock (1964) also derived a formula for an approximate $100\,(1-\alpha)\%$ upper confidence limit for $m_{\max}$, which is given as

$$\Pr\left[m_{\max} < m_{\max}^{obs} + \frac{1-\alpha}{\alpha}(m_{\max}^{obs} - m_{n-1}) \right] \cong 1-\alpha , \tag{11}$$

The nonparametric estimator (8) is very useful. The great attraction of the non-parametric approach is that it does not require specifying the functional form for the magnitude distribution. Therefore, by its nature, it is able to deal with cases with empirical distributions of any complexity: distributions which considerably violate log-linearity (1) or/and multimodal distributions, which are so characteristic for mine related seismicity (Gibowicz and Kijko, 1994). The drawback of the Robson-Whitlock estimator (8) is that it formally require knowledge of all events with magnitude above the specified level of completeness m_{min}, though, in practice, this can reduce to the knowledge of a few of the largest events.

6. Seismicity of the Selected Area and their Parameters

Figure 6.1 shows the distribution of all known seismic events with magnitude M_W=3.0 and stronger that occurred within a radius of 50 km from the KTD.

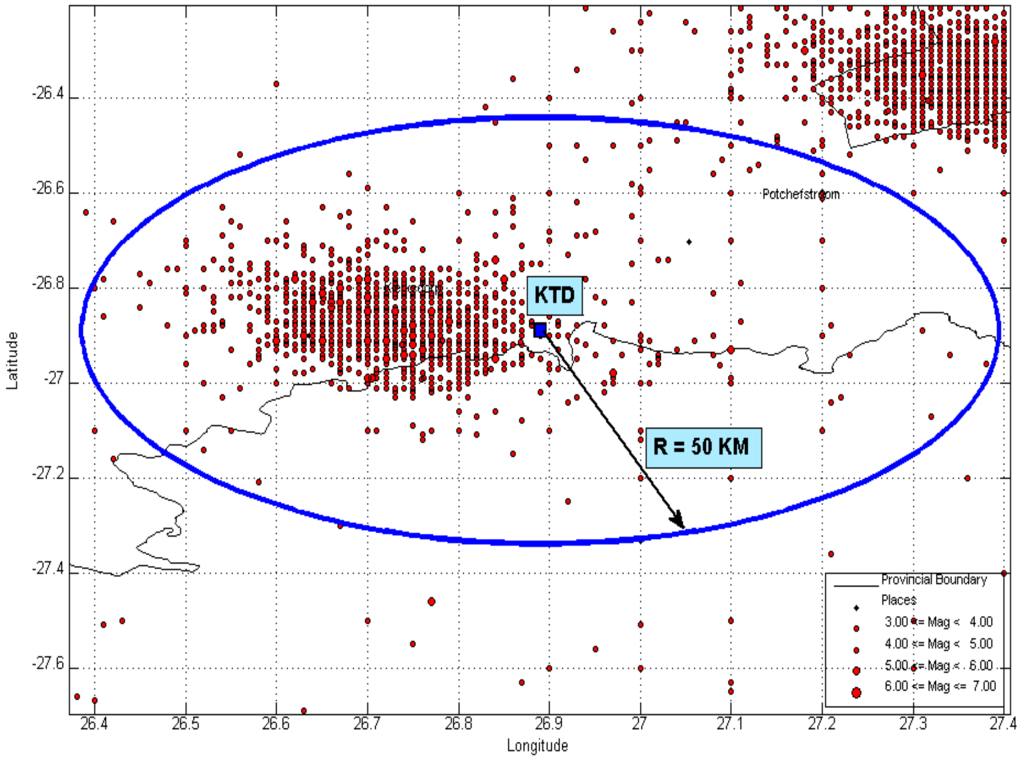

Figure 6.1 Distribution of seismic events equal to or stronger than magnitude M_W 3.0 within a 50 km radius of the KTD site (blue square).

The seismic event catalogue used in this study was compiled from several sources. After critical analysis of each of the data sources, most of the oldest records are derived from Brandt *et al.* (2005). The most recent events are mainly selected from the earthquake catalogue for southern Africa provided by the Council for Geosciences, Pretoria (Geoclips, 2013). Following procedure developed by GSHAP (Shedlock, 1999), all magnitudes were converted into moment magnitudes M_W (Lay and Wallace, 1995). The applied database of seismic events is highly incomplete and inconsistent, due to the continuous temporal change (extension/shrinking) of mine seismic networks, adjustment of processing software, mixture of different databases, different conventions of magnitude determination and different procedures used to convert different magnitude scales into unified moment magnitude M_W. The list of seismic events used in this study, from a radius of 50 km from the KTD is given in Appendix A.

The catalogue used in the analysis spans a period of ca. 50 years; from May 1966 to February 2016. The catalogue is divided into an incomplete (largest events only) and complete part, (Table 6-1).

Table 6-1 Division of the catalogue used in the analysis. $m_{\min}$ = Level of Completeness; SE = standard error of seismic event magnitude determination.

Type of catalogue	**Time Span**	$\boldsymbol{m_{\min}}$	**SE**
Incomplete – largest events	1966/05/01 – 1971/04/30	-	0.25
Complete	1971/05/01 – 2015/02/07	3.5	0.2

The recurrence parameters describing **area-characteristic** seismic hazard, the mean activity rate λ, b-value of Gutenberg-Richter were calculated according to the maximum likelihood procedure (Kijko and Sellevoll, 1989; 1992; Kijko *et al.*, 2016; and Kijko (2004). The procedure accounts for incompleteness of seismic event catalogues, uncertainty of earthquake magnitudes and uncertainty of applied earthquake recurrence model. The area-characteristic maximum possible earthquake magnitude $m_{\max}$ were calculated according to Robson and Whitlock (1964), equation (8).

The earthquake magnitude recurrence curve, $H(m)$, known as the hazard curve, is defined as the probability of a given value of magnitude, m, being exceeded at least once during a specified time interval t. Such a probability can be written as

$$H(m \mid t) = \exp\{-\lambda t[1 - F_M(m)]\}, \tag{12}$$

where $F_M(m)$ denotes the cumulative distribution function of seismic event magnitude (equation 3).

Based on seismic events recorded in vicinity of 50 km from the KTD site, the estimated maximum possible seismic event magnitude $\hat{m}_{max}$ = 5.63±0.11, the Gutenberg-Richter parameter $\hat{b}$ = 0.89 ± 0.04 and the mean activity rate $\hat{\lambda}$ = 9.3 ± 1.7 [event-s/year], for $m_{\min}$ = 3.5. The seismic hazard is specified for earthquake magnitudes within the range of 3.5 to 5.6. For each magnitude the calculated mean activity rate $\hat{\lambda}$, return period, and probabilities of exceedance in 1, 5, 10 and 25 years are listed in Appendix D. For instance, in the area within distance of 50 km from the dam site, a magnitude M_W 5.0 has mean return period of ca. 2.7 years, and 31% probability of exceedance in 1 year. It should be noted that an earthquake with magnitude M_W equal to $\widehat{m}_{max}$ = 5.63 has no associated return period.

The hazard curve, calculated for the selected area is shown in Figure 6.2. The respective mean return periods are shown in Figure 6.3. The probability of exceedance of specified magnitude within time interval 5 years, 10 years and 25 years are shown in Figure 6.3.

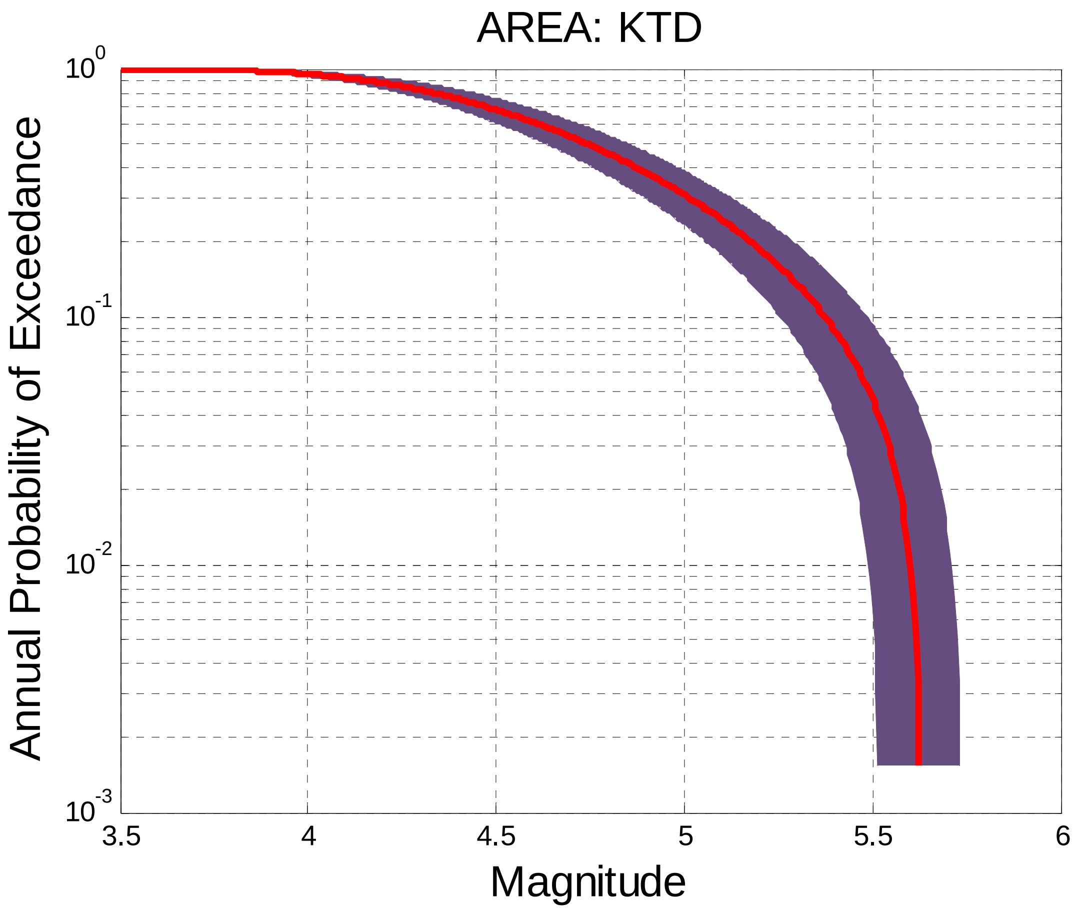

Figure 6.2 The annual probability of exceeding the specified value of seismic event magnitude for the area within 50 km from the KTD site. The red curve shows the mean probability, while the two blue curves indicate the mean probability plus or minus the standard deviation.

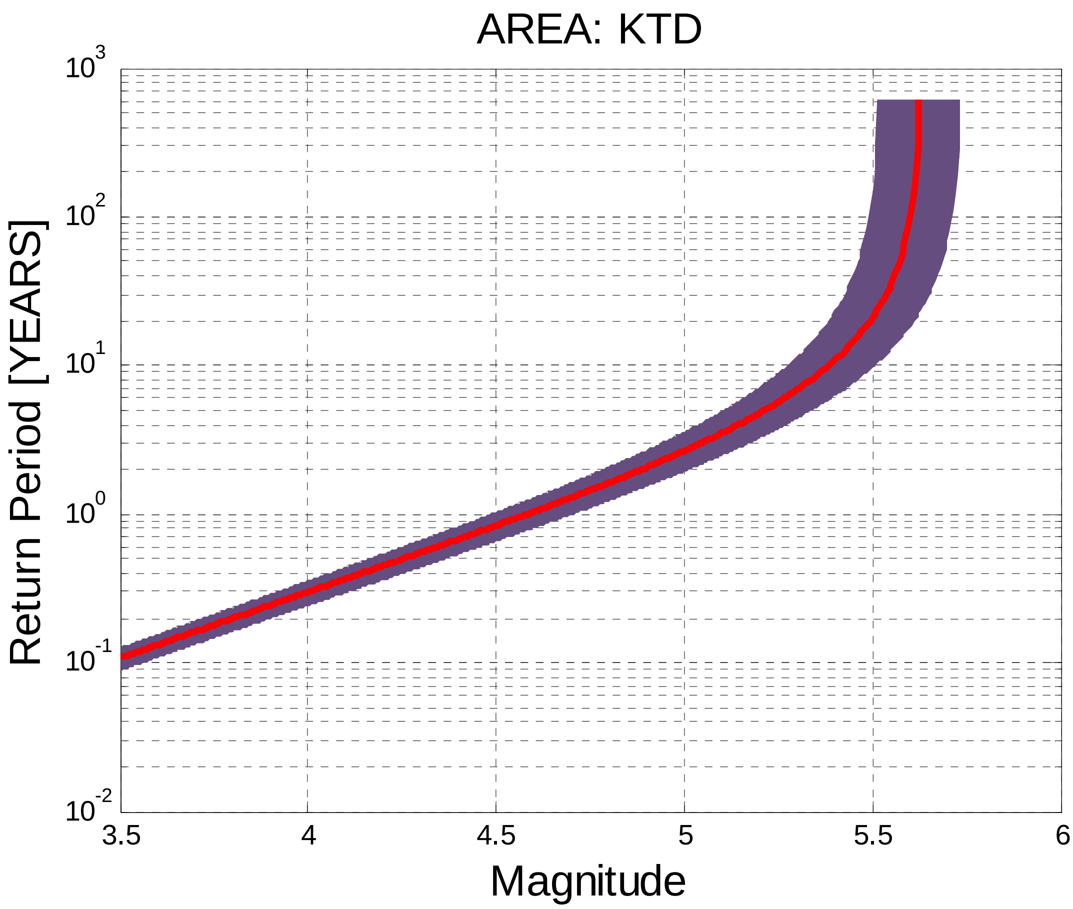

Figure 6.3 The mean return periods for seismic events occurring within the area of 50 km from the KTD site.

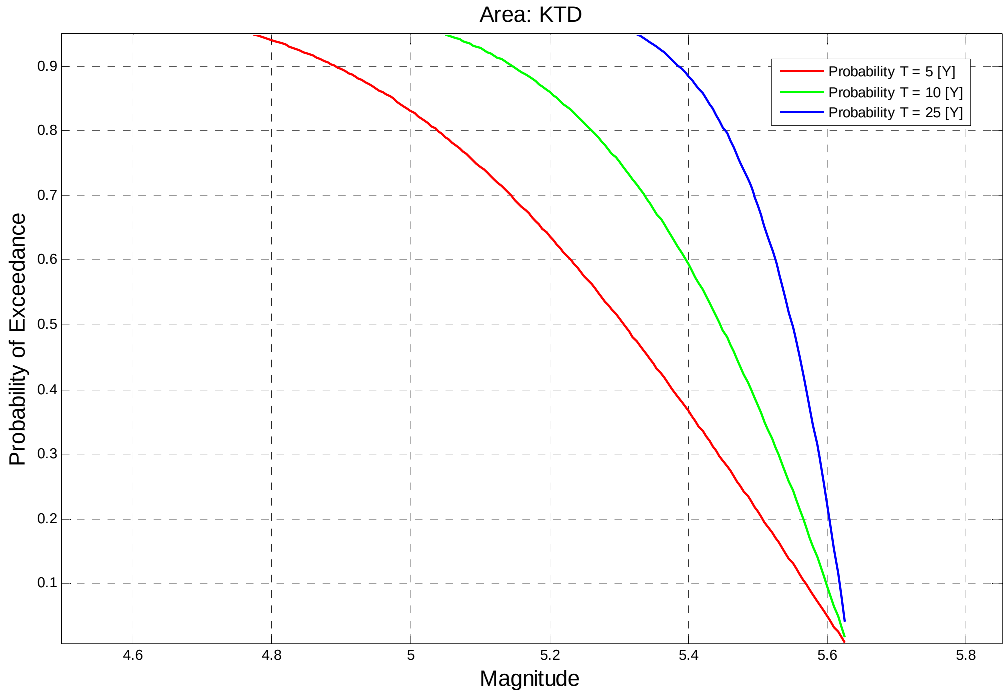

Figure 6.4. The probability of exceedance of specified value of seismic event magnitude within time interval 5, 10 and 25 years for the area within 50 km from the KTD site.

It must be noted that seismic hazard is determined by the level of ground motion (as e.g. PGA) experienced at the site of structure, not by seismic event magnitude. Strong events that occur far away are not an imposing seismic threat to the structure.

7. Applied Intensity Prediction Equations (IPEs)

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. The equations which describe the attenuation of MMI are known as the intensity prediction equations.

In this report three intensity prediction equations were used: the Modified Stable Continental Region (SCR), Regional and Global SCR.

The *SCR - Modified* IPE has a form

$$I = 4.08 + 1.27 \cdot M_W - 3.37 \cdot \log_{10}(\Delta), \tag{13}$$

where M_W denotes moment magnitude and Δ is epicentral distance in km. Equation (13) has its origin in the IPE derived for stable continental regions and modified for South African conditions (Midzi *et al*., 2015).

The IPE *Regional* has a form:

$$I = I_0 + 0.34 - 0.324 \cdot \ln(\Delta) - 0.0479 \cdot \Delta, \tag{14}$$

where MM intensity in epicentre I_0 and seismic event magnitude is given by Richter's (Richter, 1958) empirical relation (7). The IPE was developed exclusively for the Klerksdorp gold mining area (Hattingh *et al*., 2006).

Finally, the IPE *SCR - Global*,

$$I = 4.48 + 1.27 \cdot M_W - 3.37 \cdot \log_{10}(R), \tag{15}$$

where *R* denotes hypocentral distance. The IPE was developed for world-wide stable continental regions. The equation provides the lowest residuals of the MMI for small epicentral distances, not exceeded 50 km (Bakun and Scotti, 2006). Moreover, when examining the magnitude dependence, tests show that mostly, it is applicable for only small to moderate-magnitude events, say $4.5 \leq M_W \leq 5.5$.

All three applied IPE predict intensities with accuracy close to one unit of MMI.

8. Deterministic Seismic Hazard Analysis for the Kareerand Tailing Dam - Results

Following our approach, the DSHA requires the development of a particular seismic scenario, which includes the specification of an event capable of producing the strongest level of shaking.

In this report it is assumed that the maximum expected ground motion can be generated by a hypothetical seismic event situated at the epicenter of the 9th March 2005, Stilfontein event, with magnitude equal to estimated $\hat{m}_{max}$ = 5.63±0.11, located ca. 14.9 km from the dam. The area-characteristic, maximum possible seismic event magnitude was calculate according to procedure by Robson-Whitlock, as described by Kijko and Singh (2011).

Table 8-1 provides the calculated expected MMI at the site of KTD as generated by event of magnitude 5.63 with epicentral coordinates (26.890 S, 26.740 E) of the 9th March 2005, Stilfontein seismic event.

Table 8-1 Expected values of MMI at the site of seismic event of magnitude M_W = 5.63 located at the epicenter of the Stilfontein event of the 9th March 2005.

Intensity Prediction Equation (IPE)	**Predicted MMI**
SCR – Modified	7.3
Regional	6.2
SCR – Global	7.6

Since it is unclear which conversion formula of MMI into PGA are best suited for the region, two classic conversion formulas were applied (Ambraseys, 1974, and Trifunac and Brady, 1975) and the final PGA was determined by application of the logic tree formalism.

8.1 Account of uncertainties: Logic Tree Approach

The development of any complex seismotectonic model needed by seismic hazard analysis requires several essential assumptions about its parameters, especially parameters which are uncertain and allow a wide range of interpretations.

There are two types of uncertainty (variability) that can be included in seismic hazard analysis. 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. 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 hazard analysis by accounting for alternative hypothesis and models. For example, the alternative hypothesis accounts for uncertainty in earthquake source zonation, their seismic potential, seismic source hazard parameters and IPE's.

The lack of one, reliable intensity prediction equation and information about the seismic capability of tectonic faults in vicinity of the KTD are the main sources of uncertainty in this DSHA assessment.

In this report the formalism of the logic tree is applied to assess most reliable value of PGA at the site of KTD. Based on experience of work with the three IPEs, it was assumed that the probability of being correct for each of the applied IPE's are equal to 0.40 (*SCR - Modified*), 0.50 (Regional) and 0.10 (*SCR - Global*), Figure 8.3.

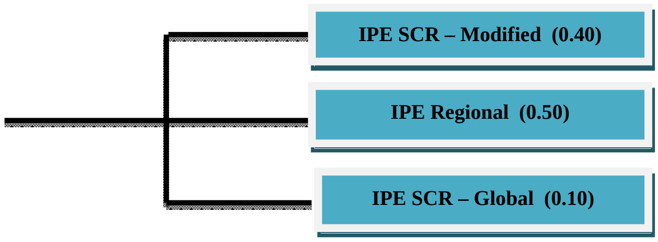

Figure 8.1 Applied logic tree. Considered three scenarios regarding applied IPEs with assigned weights.

Also, it was assumed that the weights associated with the two applied conversion formulas from MMI to PGA are the same and equal to 0.50.

Based on assigned weights to the three considered intensity prediction equations and MMI-PGA conversion formulas, the expected horizontal PGA at the site of KTD, generated by seismic event M_W = 5.63 located at the epicenter of the Stilfontein event of the 9th March 2005 is 0.152±0.098g.

9. 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 the application of the Newmark and Hall (1982) procedure. The spectra are shown in Figure 9.1. The spectra are anchored at the estimated (0.152 g) value of PGA at the KTD site.

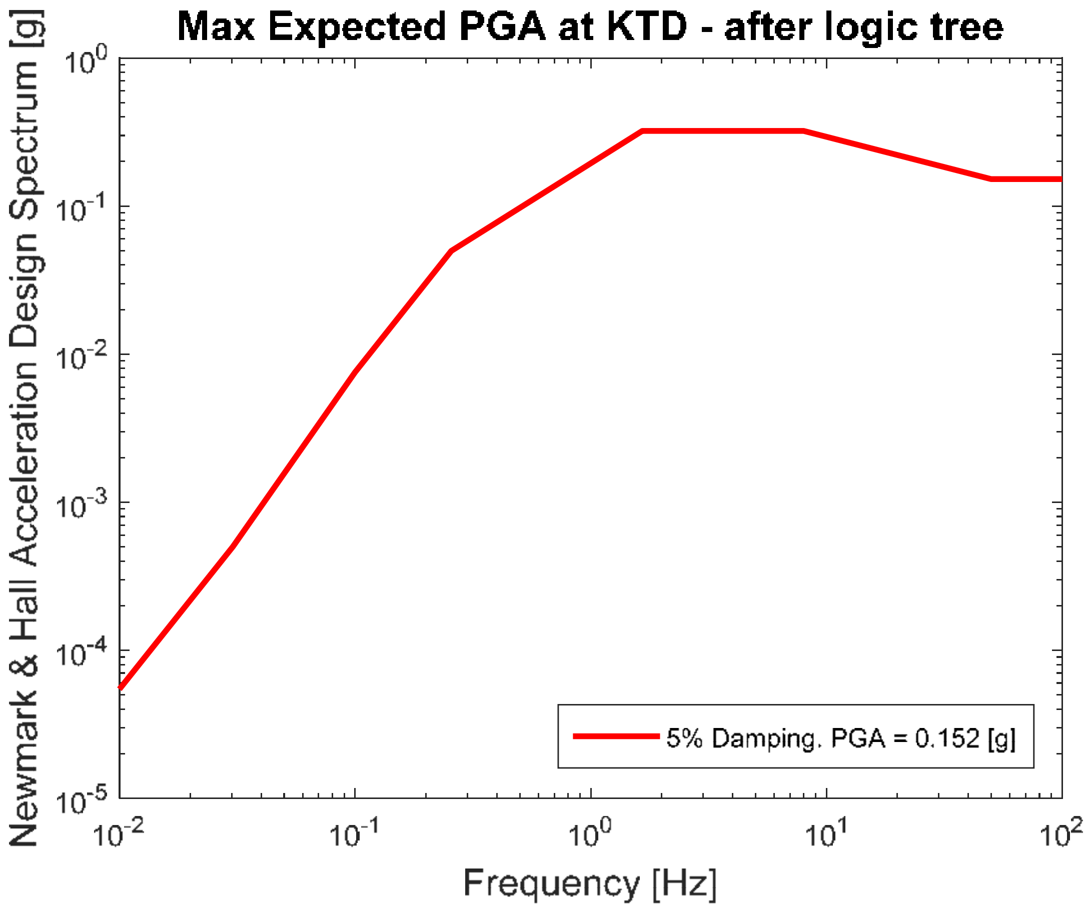

Figure 9.1 Newmark-Hall elastic design spectra (horizontal) anchored at the PGA resulting from application of logic tree procedure.

10. Conclusions

A Deterministic Seismic Hazard Analysis (desk study) has been performed for site of the Kareerand Tailing Dam, Stilfontein. All known seismic events located within a 50 km radius of the site were used in the assessment.

The controlling event is determined as an event of magnitude $M_W = 5.63 \pm 0.11$ located at the epicenter of 9th March 2005 Stilfontein event. The $M_W = 5.63 \pm 0.11$ is considered as maximum possible, mine related seismic event magnitude, characteristic to the area.

The predicted largest horizontal PGA at the site of dam is 0.152 ± 0.098 g.

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APPENDICES

Appendix A

Seismicity of area surrounding the Kareerand Tailing Dam in the radius of 50 km

YEAR	MO	DA	LAT	LONG	MAGNITUDE
1966	5	18	-27.0000	27.0000	3.30
1966	7	25	-26.8000	26.5000	3.60
1966	8	30	-27.0000	26.7000	3.20
1966	9	4	-26.5000	27.1000	3.50
1966	9	12	-26.8000	26.7000	3.20
1966	11	10	-26.5000	27.1000	3.60
1967	1	20	-27.1000	26.8000	3.80
1967	2	19	-26.8000	26.5000	3.30
1967	2	22	-26.5000	27.0000	3.60
1967	3	3	-26.8000	26.5000	3.20
1967	3	9	-26.6000	26.9000	3.70
1967	4	6	-27.0000	26.6000	3.20
1967	4	24	-26.9000	26.6000	3.10
1967	6	1	-26.9000	26.7000	3.30
1967	8	8	-26.8000	26.8000	3.20
1967	8	24	-26.5000	27.1000	3.00
1967	9	14	-26.9000	26.7000	3.30
1967	9	23	-26.6000	26.8000	3.00
1967	11	1	-27.1000	27.2000	3.00
1967	12	5	-26.5000	27.1000	3.30
1967	12	15	-26.5000	27.1000	3.10
1967	12	18	-26.5000	27.1000	3.10
1967	12	23	-26.5000	27.1000	3.10
1968	1	5	-26.8000	26.7000	3.20
1968	1	9	-26.6000	27.0000	3.30
1968	1	10	-26.7000	26.9000	3.10
1968	1	13	-26.6000	27.1000	3.20
1968	1	24	-26.7000	26.6000	3.40
1968	1	24	-26.7000	26.6000	3.40
1968	2	1	-26.8000	26.7000	3.30
1968	2	8	-27.0000	26.6000	3.80
1968	2	10	-26.7000	27.1000	3.30
1968	2	22	-26.8000	26.5000	3.00
1968	3	7	-26.7000	26.7000	3.30
1968	4	7	-26.6000	27.1000	3.50
1968	5	3	-26.5600	27.2000	3.60
1968	5	9	-26.7000	27.0000	3.40
1968	5	21	-26.5000	27.1000	3.20
1968	5	29	-26.7000	26.5000	3.10
1968	6	13	-26.7000	26.5000	3.00
1968	6	24	-26.5000	27.1000	3.00
1968	7	5	-26.8000	26.8000	3.40
1968	8	16	-26.7100	26.7000	3.80
1968	9	16	-26.9000	26.6000	3.00
1968	9	20	-26.5000	27.0000	3.00
1968	10	9	-26.6000	26.8000	3.40
1968	10	20	-26.9000	26.5000	3.70
1968	12	7	-26.5000	27.0000	3.40
1968	12	25	-26.7500	26.8700	3.90
1969	1	18	-26.5000	27.1000	3.30
1969	1	22	-26.6500	26.9900	3.50
1969	1	24	-26.8100	26.7600	3.60
1969	1	28	-26.6000	27.1000	3.40
1969	2	1	-27.2000	27.1000	3.50
1969	2	21	-26.7600	26.8200	3.70
1969	2	27	-26.6000	27.1000	3.90
1969	4	12	-26.6000	27.1000	3.30
1969	4	20	-26.8000	27.2000	4.10
1969	5	2	-27.1400	26.5200	3.40
1969	5	15	-26.6400	26.8600	3.50
1969	6	2	-26.6700	26.8600	4.00
1969	6	13	-26.5000	27.1000	3.20
1969	6	22	-26.6000	27.1000	3.20
1969	7	12	-26.5000	26.9000	3.60
1969	7	23	-27.1000	27.0000	3.20
1969	8	1	-26.5500	27.1200	3.60

1969	8	12	-27.0000	27.1000	3.10
1969	8	13	-26.5000	27.1000	3.30
1969	8	19	-26.5000	27.1000	3.10
1969	8	21	-26.9000	26.6400	3.70
1969	8	30	-27.0000	27.0000	3.00
1969	8	30	-26.7700	26.8000	4.30
1969	9	10	-27.1000	26.9000	3.40
1969	9	17	-27.1000	27.0000	3.40
1969	9	20	-26.7000	27.0000	3.40
1969	10	25	-26.9000	26.9000	3.20
1969	10	30	-26.6800	26.9000	3.40
1969	11	20	-26.5000	27.1000	3.10
1969	11	21	-26.7300	26.9200	3.50
1969	11	21	-26.7000	26.9000	3.00
1969	11	26	-26.5000	27.1000	3.20
1969	12	1	-26.7000	26.7000	3.30
1969	12	30	-26.6000	27.0000	3.10
1970	1	6	-26.6800	26.7300	3.40
1970	1	20	-26.8000	26.9000	3.80
1970	1	22	-26.8100	26.8800	3.30
1970	3	4	-26.8200	26.6500	3.20
1970	3	12	-26.8000	26.6000	3.20
1970	3	21	-27.1000	26.5000	3.00
1970	3	24	-26.8300	26.9600	3.60
1970	4	3	-26.7000	26.9000	3.40
1970	5	21	-26.9000	26.7000	3.10
1970	5	23	-26.8200	26.9000	4.95
1970	5	27	-26.6000	27.1000	3.10
1970	6	2	-26.7000	27.0000	3.10
1970	6	22	-26.7000	26.9000	3.40
1970	6	24	-26.6800	26.9500	3.20
1970	7	1	-27.1000	27.1000	4.63
1970	7	7	-27.0000	26.8000	3.20
1970	7	8	-26.8800	26.5200	3.00
1970	7	16	-26.6000	26.9000	3.00
1970	7	24	-26.7000	27.2000	3.20
1970	7	30	-27.1000	26.7000	3.00
1970	8	5	-26.6800	26.9500	3.30
1970	8	6	-27.0000	26.6000	3.20
1970	8	16	-27.2000	27.1000	3.00
1970	8	25	-26.8200	26.6500	3.50
1970	9	3	-26.8100	26.8800	3.20
1970	9	11	-27.0400	27.2100	3.30
1970	9	12	-27.0000	26.8000	3.30
1970	9	25	-26.8400	26.8100	4.84
1970	9	25	-26.8300	26.8600	3.60
1970	9	29	-26.5900	27.0000	3.90
1970	10	17	-26.9000	26.9000	3.00
1970	10	26	-26.6000	27.1000	3.50
1970	10	31	-26.7800	26.8500	5.60
1970	11	9	-26.6000	27.2000	3.20
1970	11	13	-26.9000	27.2000	3.30
1970	11	19	-26.9000	26.9000	3.20
1970	11	19	-26.9000	26.9000	3.40
1970	11	27	-26.8200	26.6500	3.10
1970	12	6	-27.2000	27.0000	3.10
1970	12	25	-26.8000	26.5000	3.10
1971	1	10	-26.7700	26.7600	3.00
1971	1	12	-26.8000	26.6000	3.10
1971	1	14	-26.9000	27.0000	3.10
1971	1	19	-26.9300	26.5500	3.50
1971	1	23	-26.8000	26.4000	3.00
1971	1	23	-26.6800	26.7200	3.50
1971	1	25	-26.7600	26.7500	3.80
1971	2	1	-26.7600	26.7900	3.80
1971	2	5	-26.7600	26.7900	3.20
1971	2	21	-26.6900	26.9300	3.20
1971	2	22	-26.8500	26.6200	3.20
1971	2	24	-26.8200	26.6500	3.10
1971	2	27	-27.0100	26.6700	3.20
1971	3	6	-26.5500	27.0100	3.10
1971	3	16	-26.6300	26.8600	3.30
1971	4	10	-26.6900	26.9400	3.50
1971	4	14	-26.6800	26.9500	3.30
1971	5	4	-26.7100	26.8700	3.50
1971	5	5	-26.7900	27.1100	3.20
1971	6	6	-27.1000	27.1000	3.40
1971	6	6	-26.7700	26.7700	3.30
1971	6	23	-26.6700	26.5600	3.30
1971	7	21	-26.7600	26.8700	3.30
1971	9	1	-26.6600	26.7500	3.80
1971	9	6	-26.6400	26.8100	3.30
1971	9	9	-26.5600	26.6800	3.70
1971	9	10	-26.6400	26.8400	3.60
1971	9	14	-26.9200	26.6800	3.40
1971	10	18	-26.6900	26.8400	3.40
1971	11	12	-26.7200	26.7400	3.60
1972	2	7	-26.9300	26.7900	3.70
1972	3	17	-26.8100	26.7700	4.10
1972	5	9	-26.8900	26.6600	3.20
1972	5	10	-26.8100	26.7000	3.60
1972	5	17	-26.8000	26.7000	3.30
1972	5	17	-26.4500	26.8400	3.20
1972	6	20	-26.7800	26.6100	3.30
1972	7	9	-26.8100	26.8800	3.30

1972	8	5	-26.8500	26.7200	3.40
1972	8	16	-26.7400	26.6900	3.70
1972	8	24	-26.7400	27.0300	3.30
1972	8	25	-26.9000	26.7200	3.30
1972	9	7	-26.7900	26.8100	3.70
1972	10	14	-26.5000	26.9300	3.30
1972	11	1	-26.9000	26.8700	4.40
1972	11	12	-26.9000	26.9200	3.20
1972	11	14	-26.8900	26.7800	3.40
1972	12	8	-26.8800	26.5200	3.10
1972	12	10	-26.6500	26.6700	3.70
1972	12	18	-26.6100	26.8600	4.00
1972	12	27	-26.8700	26.7900	3.80
1973	1	31	-26.7900	26.7100	3.30
1973	3	8	-26.8500	26.7100	3.30
1973	4	15	-26.8600	26.7600	3.30
1973	4	16	-26.7700	26.7700	3.90
1973	5	23	-26.7600	26.4800	3.30
1973	5	31	-26.8400	26.8100	3.30
1973	6	9	-26.8800	26.6400	3.10
1973	6	21	-26.9600	27.0200	3.20
1973	6	22	-26.6900	26.6100	3.30
1973	8	7	-26.7800	26.7700	4.10
1973	8	14	-26.7600	26.7000	3.80
1973	8	31	-26.8100	26.9000	3.30
1973	9	30	-26.8100	26.6600	3.50
1973	10	5	-26.8200	26.9500	3.50
1973	11	7	-26.9400	26.9500	4.30
1973	11	13	-26.7900	26.7800	4.20
1973	11	13	-26.7800	26.7300	3.80
1973	12	15	-26.5800	26.9900	3.50
1973	12	19	-26.7500	26.9900	4.95
1973	12	30	-26.8600	26.8000	3.40
1974	1	5	-26.5300	26.9400	3.20
1974	1	7	-26.7800	26.9400	3.50
1974	3	17	-26.8300	26.7500	4.20
1974	4	3	-26.7200	26.6900	3.30
1974	4	17	-26.8100	26.8200	3.40
1974	6	14	-26.8000	26.5200	4.10
1974	6	23	-26.8800	26.7300	3.50
1974	7	7	-26.8600	26.8500	3.40
1974	7	23	-26.8200	26.9200	4.80
1974	8	13	-26.8100	26.7800	3.40
1974	12	9	-26.8100	26.7700	3.40
1974	12	9	-26.7800	26.7500	3.40
1974	12	15	-26.8700	26.5400	3.80
1975	2	8	-26.9200	26.7200	3.80
1975	2	26	-26.7000	26.5900	3.50
1975	5	31	-26.7900	26.8300	3.50
1975	6	4	-26.7200	26.7600	3.90
1975	7	15	-27.0000	26.9600	3.40
1975	7	15	-26.8300	26.8200	3.70
1975	8	19	-26.8300	26.7600	3.60
1975	10	27	-26.9000	26.7700	3.60
1975	12	29	-26.9300	26.8100	3.40
1976	1	19	-26.7000	26.5000	3.20
1976	1	24	-26.7600	26.7200	3.50
1976	1	26	-26.8300	26.9000	3.60
1976	1	29	-26.4600	27.0400	3.50
1976	2	8	-26.5300	27.0900	3.50
1976	3	6	-27.0700	27.3200	3.30
1976	3	13	-26.8900	26.7600	3.50
1976	4	1	-27.2500	26.9200	3.30
1976	6	21	-26.8900	27.3100	3.50
1976	6	30	-26.8900	26.8600	3.50
1976	7	31	-26.8100	26.7000	3.80
1976	7	31	-26.7700	26.4500	3.80
1976	8	3	-26.9200	26.7700	3.70
1976	8	4	-26.8300	26.8200	3.40
1976	9	4	-26.7800	26.8200	3.50
1976	9	24	-26.8700	26.9100	3.80
1976	9	24	-26.7700	26.8400	3.50
1976	12	10	-26.9400	27.3400	3.50
1976	12	18	-26.7800	26.5900	3.50
1977	1	8	-26.7700	26.7400	4.20
1977	1	20	-26.8000	26.8000	3.10
1977	2	17	-26.8700	26.8200	3.30
1977	3	6	-26.6600	26.5500	4.20
1977	4	7	-26.9000	26.6500	3.80
1977	4	7	-26.8900	26.7400	5.00
1977	4	19	-26.9100	26.9700	3.50
1977	4	26	-26.8600	26.7500	3.70
1977	6	21	-26.9900	27.1000	3.40
1977	7	11	-26.8600	26.7500	4.00
1977	8	8	-26.9700	26.8000	3.00
1977	9	2	-26.7800	26.7200	3.80
1977	9	20	-26.8400	26.7900	3.00
1977	9	26	-26.7700	26.6200	3.60
1977	9	27	-27.0200	26.7500	3.30
1977	10	6	-26.8800	26.6900	4.20
1977	10	13	-26.8700	26.7600	3.00
1977	10	31	-26.8700	26.7800	3.10
1977	11	19	-26.5000	26.9700	3.50
1977	12	1	-26.9200	26.6900	3.30
1977	12	6	-26.9100	26.6300	4.10

1977	12	20	-26.8800	26.4800	3.10
1978	1	19	-26.8600	26.7200	4.30
1978	2	4	-26.8900	26.7300	3.40
1978	2	8	-26.9300	26.8400	3.20
1978	2	18	-26.4900	27.0100	3.60
1978	2	19	-27.0800	26.8700	3.00
1978	2	24	-26.8000	26.7000	3.30
1978	3	18	-26.8100	26.7100	3.70
1978	3	31	-27.0600	26.8000	3.30
1978	4	7	-26.9800	26.6700	3.00
1978	4	26	-26.8100	26.7400	3.90
1978	5	8	-26.9600	26.9000	3.00
1978	5	10	-26.7000	26.7000	3.20
1978	5	27	-26.8800	26.8200	4.00
1978	6	7	-26.9600	26.8600	3.40
1978	6	15	-26.8100	26.6700	3.50
1978	6	24	-27.0300	27.2200	3.40
1978	7	21	-26.8700	26.6800	3.50
1978	8	22	-26.8600	26.6200	3.50
1978	8	29	-26.8000	26.6400	3.70
1978	9	17	-26.8900	26.7200	3.30
1978	10	11	-27.0200	26.9600	3.50
1978	10	12	-26.9000	26.9000	3.50
1978	10	21	-26.7800	26.6800	3.60
1978	11	2	-26.7600	26.6900	3.90
1978	12	9	-26.7800	26.7900	3.90
1979	1	24	-26.8500	26.6500	4.95
1979	1	25	-26.8600	26.7200	4.00
1979	1	25	-26.8100	26.6500	5.28
1979	3	2	-26.8100	26.6600	3.60
1979	3	31	-26.8300	26.7100	3.50
1979	4	5	-26.8300	26.6500	3.10
1979	4	6	-26.8500	26.7300	5.17
1979	4	7	-26.9500	26.7500	3.30
1979	4	13	-26.8800	26.7500	3.20
1979	5	23	-26.7900	26.7700	3.90
1979	6	18	-26.8300	26.6700	3.60
1979	7	8	-26.7300	26.6300	3.30
1979	7	11	-26.9300	26.7000	3.10
1979	8	18	-26.8200	26.8200	3.70
1979	9	23	-26.9700	26.6800	3.10
1979	10	2	-26.8400	26.6600	4.00
1979	10	4	-26.8400	26.7800	3.60
1979	10	12	-26.9000	26.7500	3.30
1979	11	7	-26.7300	26.6600	3.50
1979	11	16	-26.8700	26.7200	3.70
1979	12	13	-26.9000	26.9100	3.50
1980	1	18	-26.8300	26.7200	3.30
1980	2	4	-26.4900	27.0400	3.20
1980	2	6	-26.8200	26.6500	3.70
1980	2	27	-27.0200	26.8900	3.20
1980	2	28	-26.9400	26.6900	3.20
1980	3	4	-26.8900	26.7600	3.80
1980	3	6	-26.8600	26.4100	3.70
1980	4	11	-26.7600	26.5700	3.00
1980	4	26	-26.8700	26.6500	3.20
1980	4	30	-26.9000	26.7200	3.60
1980	5	6	-26.9300	27.0000	4.84
1980	5	13	-26.8800	26.6100	3.20
1980	5	13	-26.8700	26.8400	3.20
1980	5	19	-26.8400	26.6900	3.30
1980	6	12	-26.9800	26.9700	5.06
1980	6	13	-26.8600	26.8100	3.30
1980	6	13	-26.8500	26.7700	5.06
1980	7	9	-26.8600	26.7600	3.40
1980	7	10	-26.8800	26.7500	3.90
1980	7	18	-26.7800	26.7000	3.60
1980	7	26	-26.8700	26.8500	3.50
1980	8	2	-26.9900	26.8100	3.00
1980	8	28	-26.9000	26.7000	3.90
1980	9	14	-26.7600	26.6800	3.60
1980	9	14	-26.7500	26.6600	3.40
1980	9	25	-26.8500	26.6800	3.00
1980	10	23	-26.8300	26.7200	3.30
1980	11	4	-26.8400	26.6800	3.00
1980	11	6	-26.7000	26.7000	3.60
1980	11	7	-26.7700	26.7200	3.40
1980	11	8	-26.8400	26.7100	3.30
1980	11	14	-26.8400	26.7900	3.20
1980	11	14	-26.7600	26.7900	3.30
1980	11	20	-26.8000	26.7300	3.80
1980	12	11	-26.8100	26.8000	3.50
1981	1	24	-26.8900	26.8100	3.00
1981	1	30	-26.8500	26.7100	3.00
1981	2	2	-26.9100	26.7100	3.10
1981	2	5	-26.9100	26.7400	3.00
1981	2	8	-26.8100	26.8200	3.60
1981	2	18	-26.7900	26.6500	4.95
1981	3	3	-26.9200	26.7500	3.20
1981	3	14	-26.8600	26.7500	3.40
1981	3	16	-26.6200	26.9300	3.50
1981	4	4	-26.8700	26.7400	3.10
1981	4	15	-26.7700	26.6600	3.30
1981	4	22	-26.7400	27.0200	3.10
1981	5	7	-26.7600	26.5900	3.30

1981	5	9	-26.8000	26.5900	3.50
1981	5	12	-26.7900	26.6900	3.10
1981	5	21	-26.8900	26.7600	3.10
1981	5	27	-26.8700	26.8800	3.20
1981	5	30	-26.7300	26.6300	3.00
1981	6	4	-26.8500	26.8600	3.10
1981	6	5	-26.8500	26.7400	3.00
1981	6	18	-26.5400	27.1300	3.40
1981	7	5	-26.8800	26.6600	3.10
1981	7	13	-26.8000	26.6700	3.20
1981	8	7	-26.9400	26.8800	3.10
1981	8	9	-26.8000	26.7500	3.30
1981	8	14	-26.8000	26.8000	3.90
1981	9	5	-26.8300	26.6900	3.40
1981	9	19	-26.7600	26.6900	3.30
1981	10	8	-26.9500	26.8400	5.70
1981	10	22	-26.8800	26.7700	3.10
1981	11	28	-26.9800	26.7500	3.20
1981	11	30	-26.8600	26.7300	3.30
1981	12	4	-26.5600	27.0800	3.10
1981	12	6	-26.4900	27.1200	3.30
1981	12	24	-26.8500	26.6900	3.30
1981	12	24	-26.8100	26.7700	3.30
1981	12	25	-26.7800	26.5800	3.20
1981	12	28	-26.8300	26.6800	3.10
1982	1	5	-26.8500	26.6700	3.10
1982	1	6	-26.8500	26.6400	3.00
1982	1	11	-26.7600	26.5200	3.50
1982	1	18	-26.9100	26.7800	3.00
1982	1	29	-26.7700	26.6300	3.30
1982	1	29	-26.7500	26.6600	3.20
1982	2	10	-26.8300	26.7200	3.10
1982	2	10	-26.8000	26.6900	3.40
1982	2	16	-26.7800	26.6200	3.50
1982	3	2	-26.5900	26.7000	3.20
1982	3	31	-26.8600	26.7500	3.10
1982	4	2	-26.8800	26.7500	3.20
1982	4	9	-26.7500	26.5900	4.52
1982	4	26	-26.7900	26.6900	3.40
1982	4	27	-26.8500	26.6400	3.80
1982	5	10	-26.8500	26.6200	3.00
1982	5	28	-26.8900	26.6900	3.60
1982	5	28	-26.8600	26.6600	3.20
1982	6	18	-26.8900	26.7900	3.70
1982	6	20	-26.8700	26.6700	3.10
1982	6	23	-26.8300	26.7200	3.20
1982	6	27	-26.7600	26.5400	3.60
1982	6	28	-26.8800	26.8100	3.40
1982	9	17	-26.9000	26.7300	3.10
1982	9	17	-26.8300	26.6700	3.30
1982	9	29	-26.8500	26.7000	3.00
1982	10	1	-26.8500	26.7100	3.60
1982	11	1	-26.8800	26.7100	3.50
1982	11	12	-26.9100	26.7200	5.17
1982	11	29	-26.9500	26.7500	3.30
1982	12	6	-26.8800	26.7300	3.20
1982	12	11	-26.8700	26.6700	4.74
1982	12	11	-26.8600	26.6800	3.10
1982	12	11	-26.7300	26.7000	4.09
1982	12	11	-26.7100	26.5500	3.10
1982	12	16	-26.8900	26.7300	3.00
1982	12	21	-26.8800	26.7100	3.80
1982	12	21	-26.8500	26.7200	3.20
1982	12	28	-26.6900	26.5400	3.40
1983	1	3	-26.8200	26.6600	4.74
1983	1	5	-26.8100	26.6600	3.20
1983	1	14	-26.8800	26.8600	3.20
1983	2	8	-26.8200	26.6100	3.70
1983	2	18	-26.9900	26.8000	3.30
1983	3	19	-26.9100	26.7600	3.40
1983	4	4	-26.8800	26.6500	3.40
1983	4	8	-26.9500	26.7100	3.00
1983	4	8	-26.8900	26.6800	3.00
1983	4	13	-26.8700	26.6400	3.70
1983	4	14	-26.8800	26.6200	4.63
1983	4	14	-26.8700	26.7500	3.20
1983	4	17	-26.8600	26.7100	3.00
1983	4	24	-26.9200	26.7500	3.20
1983	4	25	-26.8500	26.7000	3.10
1983	4	27	-26.8800	26.7300	3.50
1983	5	5	-26.8900	26.7300	3.10
1983	5	17	-26.8300	26.6600	5.06
1983	5	18	-26.8600	26.7700	3.50
1983	5	19	-26.8700	26.7300	3.00
1983	5	28	-26.8500	26.7500	3.10
1983	6	5	-26.8900	26.7300	3.10
1983	6	6	-26.8800	26.7500	5.39
1983	6	6	-26.8700	26.7400	4.30
1983	6	11	-26.9200	26.7200	3.30
1983	6	17	-26.9500	26.7900	3.40
1983	6	20	-26.9500	26.6700	3.30
1983	6	21	-26.9600	26.8500	3.10
1983	6	27	-27.0000	26.7200	3.20
1983	6	29	-26.8000	26.6900	3.30
1983	6	30	-26.8800	26.8100	3.00

1983	7	7	-26.9100	26.7000	3.20
1983	7	7	-26.8500	26.6100	3.40
1983	7	9	-26.9600	26.7900	3.00
1983	8	3	-26.8900	26.7000	3.00
1983	8	6	-26.8300	26.6200	3.40
1983	8	15	-26.9500	26.7300	3.40
1983	9	7	-26.9500	26.7200	3.10
1983	9	11	-26.8200	26.7500	4.00
1983	9	18	-26.9100	26.7100	3.30
1983	9	26	-26.7500	26.6800	3.00
1983	12	7	-26.8800	26.6200	4.84
1984	1	28	-26.9000	26.6300	5.08
1984	1	28	-26.8200	26.7000	5.28
1984	2	3	-26.9700	26.8500	3.40
1984	2	9	-27.0000	26.8000	3.10
1984	2	14	-26.8300	26.7500	3.00
1984	2	22	-26.7100	26.6300	3.30
1984	2	23	-26.8300	26.7100	3.30
1984	2	24	-26.8000	26.6100	3.40
1984	3	5	-26.8000	26.6300	3.90
1984	3	15	-26.9600	26.7900	3.00
1984	3	27	-26.8700	26.6800	3.00
1984	3	30	-26.9400	26.8700	3.00
1984	4	17	-26.8700	26.6900	3.10
1984	4	24	-26.9200	26.9400	3.20
1984	5	1	-26.8800	26.8400	3.10
1984	5	2	-26.9000	26.7700	3.30
1984	5	4	-26.8300	26.6300	4.84
1984	5	16	-26.9200	26.6900	3.00
1984	5	18	-26.9500	26.7600	3.00
1984	6	9	-26.9400	26.7800	3.00
1984	6	20	-26.9100	26.7600	3.10
1984	6	20	-26.8800	26.7600	3.10
1984	6	25	-26.9400	26.7800	3.40
1984	7	4	-26.9200	26.7100	3.40
1984	7	5	-26.8100	26.7500	4.00
1984	7	13	-26.8800	26.7500	3.20
1984	7	24	-26.8400	26.5700	3.10
1984	7	28	-26.8500	26.5300	3.00
1984	7	29	-26.8400	26.4500	3.00
1984	7	31	-26.9300	26.7400	3.00
1984	8	5	-26.8600	26.8100	3.10
1984	8	9	-26.8200	26.7000	3.00
1984	8	11	-26.8300	26.6400	5.06
1984	8	11	-26.8000	26.6800	3.60
1984	8	11	-26.8000	26.7200	3.90
1984	8	15	-26.8700	26.6400	3.50
1984	9	14	-26.9600	26.7000	3.10
1984	9	15	-26.7800	26.6600	3.80
1984	9	18	-26.9800	26.7200	3.00
1984	9	22	-26.8300	26.6100	3.20
1984	10	4	-26.8000	26.6800	3.50
1984	10	15	-26.7000	26.7400	3.40
1984	10	18	-26.8100	26.6100	3.70
1984	10	30	-26.9400	26.8100	3.30
1984	11	19	-26.9600	26.7200	3.10
1984	11	22	-26.9500	26.8100	3.00
1984	11	24	-26.8100	26.7000	3.20
1984	11	30	-26.8800	26.6900	3.30
1984	12	4	-26.8500	26.7900	3.60
1984	12	15	-26.8900	26.7100	3.70
1984	12	18	-26.8500	26.7600	3.50
1984	12	26	-26.8900	26.7500	3.30
1984	12	28	-26.9300	26.7600	3.00
1985	1	4	-26.7500	26.5700	3.20
1985	1	14	-26.8500	26.6700	3.60
1985	1	16	-26.8100	26.6300	3.50
1985	1	17	-26.9300	26.7300	3.20
1985	1	18	-26.9400	26.8200	3.20
1985	1	19	-26.7700	26.5600	3.10
1985	2	6	-26.8300	26.8300	3.30
1985	3	2	-26.7700	26.7000	3.40
1985	3	6	-26.8500	26.7100	3.60
1985	3	8	-26.8500	26.6400	3.40
1985	3	20	-26.8800	26.7400	3.70
1985	3	22	-26.8900	26.7300	3.40
1985	3	25	-26.8900	26.7400	3.50
1985	3	29	-26.8300	26.7500	3.00
1985	4	2	-26.8600	26.6800	3.20
1985	4	6	-26.7800	26.7600	3.70
1985	4	9	-26.9200	26.7700	3.00
1985	4	14	-26.8100	26.6400	3.20
1985	4	14	-26.8000	26.6800	3.40
1985	4	18	-26.8700	26.8100	3.00
1985	4	21	-26.7200	26.7300	3.20
1985	4	24	-26.8000	26.6100	4.95
1985	5	10	-26.9500	26.8000	3.10
1985	5	16	-26.9700	26.8000	3.00
1985	5	26	-26.7900	26.6500	4.95
1985	6	7	-26.8200	26.6600	3.10
1985	6	8	-26.7400	26.6700	4.30
1985	6	22	-26.7900	26.7400	3.40
1985	7	3	-26.9100	26.7300	3.30
1985	7	4	-26.7700	26.6000	4.20
1985	7	6	-26.7700	26.6000	3.20

1985	7	8	-26.8800	26.7400	3.00
1985	7	16	-26.9300	26.7400	3.10
1985	7	30	-26.8500	26.6800	4.63
1985	7	30	-26.8300	26.7800	3.10
1985	8	3	-26.9100	26.7600	3.00
1985	8	8	-26.9000	26.6900	3.20
1985	8	9	-26.9200	26.7500	3.10
1985	8	11	-26.7800	26.7500	3.80
1985	8	13	-26.8800	26.7700	3.10
1985	8	27	-26.8100	26.7100	3.00
1985	8	28	-26.8900	26.6700	3.00
1985	9	5	-26.9400	26.8200	3.10
1985	9	20	-26.8600	26.6800	3.30
1985	9	21	-26.8200	26.6700	3.20
1985	9	24	-26.9300	26.7800	3.10
1985	10	2	-26.9800	26.7200	3.20
1985	10	2	-26.8100	26.6300	3.50
1985	10	6	-26.9000	26.7100	3.10
1985	10	8	-26.9200	26.6100	3.40
1985	10	9	-26.8900	26.6400	3.30
1985	10	11	-26.9100	26.7000	3.10
1985	10	27	-26.8000	26.6000	3.30
1985	11	1	-26.9100	26.7000	3.30
1985	11	2	-26.7600	26.7800	3.50
1985	11	9	-26.8800	26.7800	3.30
1985	11	21	-26.9200	26.7000	3.10
1985	12	19	-26.9100	26.7100	3.10
1985	12	20	-26.8700	26.8000	3.00
1985	12	27	-26.8500	26.8500	3.00
1986	1	1	-26.8000	26.6700	5.17
1986	1	9	-26.9000	26.8300	3.30
1986	1	9	-26.8700	26.7500	4.52
1986	1	22	-26.8300	26.8700	4.74
1986	1	27	-26.8100	26.7100	4.63
1986	1	27	-26.8000	26.8200	3.70
1986	1	29	-26.8900	26.6900	3.10
1986	2	23	-26.8000	26.6500	4.00
1986	2	24	-26.7700	26.5900	3.40
1986	3	19	-26.9100	26.8200	3.20
1986	3	21	-26.8700	26.8100	3.20
1986	4	9	-26.8800	26.5700	3.00
1986	4	9	-26.8700	26.5900	3.20
1986	4	19	-26.9400	26.7300	3.50
1986	4	21	-26.8900	26.7100	3.10
1986	4	22	-26.9800	26.6300	3.20
1986	5	14	-26.8900	26.7400	3.20
1986	5	29	-26.9500	26.7900	3.00
1986	6	4	-26.7700	26.7300	3.10
1986	6	8	-26.9700	26.8100	3.10
1986	6	29	-26.8400	26.6900	3.20
1986	7	8	-26.8800	26.7300	3.30
1986	7	19	-26.9300	26.7100	3.00
1986	7	21	-26.8900	26.7100	3.10
1986	7	22	-26.9200	26.6900	4.52
1986	7	31	-26.9500	26.7600	3.00
1986	8	8	-26.9000	26.7500	3.30
1986	8	9	-26.9600	26.7900	3.00
1986	8	11	-26.9100	26.6000	5.17
1986	8	21	-26.8900	26.7000	3.30
1986	8	26	-26.8800	26.7500	3.00
1986	8	29	-26.9500	26.7000	3.30
1986	9	24	-26.7800	26.6900	3.40
1986	10	2	-26.8400	26.7300	3.20
1986	10	5	-26.8900	26.7200	3.00
1986	10	10	-26.9500	26.7800	3.00
1986	10	28	-27.0000	26.7500	3.10
1986	10	28	-26.9400	26.7500	5.70
1986	11	6	-27.0000	26.8000	3.10
1986	11	7	-26.9200	26.7200	3.30
1986	11	13	-26.9000	26.7500	5.28
1986	11	19	-26.8600	26.6600	4.10
1986	11	24	-27.0300	26.7900	3.20
1986	12	8	-26.8500	26.6300	3.10
1986	12	9	-26.9100	26.6900	3.00
1987	2	6	-26.8800	26.7500	3.30
1987	3	4	-26.9100	26.7900	3.00
1987	3	7	-26.9900	26.7400	3.00
1987	3	17	-26.8900	26.7100	3.20
1987	3	20	-26.7800	26.6200	3.00
1987	4	2	-26.9000	26.6300	3.10
1987	4	9	-26.9700	26.7700	3.10
1987	4	9	-26.9400	26.7500	3.30
1987	4	12	-26.8300	26.6800	3.20
1987	4	14	-26.8500	26.7000	5.17
1987	5	6	-26.9400	26.8300	3.00
1987	5	20	-26.8800	26.6900	3.10
1987	5	20	-26.8600	26.7200	3.70
1987	5	26	-26.9300	26.7700	3.60
1987	5	29	-26.8400	26.6600	5.06
1987	7	4	-26.9100	26.7200	3.40
1987	7	6	-26.8700	26.6200	3.30
1987	7	24	-26.8500	26.6800	3.30
1987	7	25	-26.8100	26.7700	3.00
1987	7	30	-26.9000	26.8700	3.10
1987	7	30	-26.7800	26.6900	5.17

1987	8	4	-26.8500	26.7100	3.50
1987	8	25	-26.8500	26.7800	3.10
1987	9	7	-26.9300	26.7200	3.60
1987	9	12	-26.9300	26.7400	3.00
1987	9	12	-26.8400	26.6300	3.60
1987	9	30	-26.7800	26.7000	5.06
1987	10	12	-26.9300	26.6600	3.10
1987	11	22	-26.7800	26.7300	3.10
1987	12	19	-26.7600	26.4900	3.60
1987	12	23	-26.9700	26.8100	3.00
1987	12	28	-26.8300	26.6600	3.30
1988	1	5	-26.9100	26.7000	5.28
1988	1	6	-26.8200	26.5500	3.20
1988	1	30	-26.8400	26.5900	3.40
1988	1	31	-26.8900	26.6400	3.00
1988	2	26	-26.8500	26.6400	4.09
1988	3	4	-26.9700	26.8100	3.10
1988	3	12	-26.9600	26.5700	3.10
1988	3	12	-26.8000	26.6300	3.50
1988	3	16	-26.8000	26.6100	3.20
1988	3	24	-26.8700	26.6200	3.20
1988	4	11	-26.8200	26.7700	3.00
1988	4	28	-26.8500	26.7400	3.00
1988	5	15	-26.8200	26.5800	3.50
1988	6	4	-26.8900	26.7000	3.30
1988	6	4	-26.8200	26.7200	3.20
1988	6	16	-26.7800	26.7400	4.00
1988	7	5	-26.8500	26.7000	3.20
1988	7	22	-26.7900	26.6300	3.10
1988	7	31	-26.8300	26.8000	3.10
1988	8	9	-26.9500	26.7900	3.10
1988	8	11	-26.8400	26.6400	3.70
1988	8	17	-26.8400	26.5900	3.60
1988	8	31	-26.8100	26.7100	3.40
1988	9	11	-26.8600	26.7300	3.40
1988	9	12	-26.8900	26.6500	4.84
1988	9	15	-26.8500	26.6800	3.50
1988	9	18	-26.8400	26.8200	3.10
1988	10	8	-26.8300	26.6300	3.00
1988	10	13	-26.8200	26.7000	3.10
1988	10	14	-26.8400	26.7300	3.10
1988	10	28	-26.9100	26.7900	3.10
1988	10	28	-26.8700	26.8400	3.10
1988	11	3	-26.8300	26.7400	3.20
1988	11	14	-26.8700	26.6700	3.10
1988	11	28	-26.9700	26.6400	3.10
1988	12	8	-26.8700	26.6300	3.10
1988	12	15	-26.8300	26.7900	4.95
1988	12	22	-26.9500	26.6500	4.74
1988	12	23	-26.8300	26.6500	3.20
1989	1	4	-26.9000	26.7700	3.20
1989	1	20	-26.8100	26.7200	3.30
1989	2	9	-26.9200	26.7300	3.00
1989	2	20	-26.8300	26.6900	3.60
1989	3	10	-26.9600	26.8100	3.00
1989	3	14	-26.8800	26.7100	3.20
1989	3	15	-26.8900	26.7600	3.00
1989	3	16	-26.8200	26.7300	3.10
1989	3	30	-26.8100	26.7700	4.84
1989	4	2	-26.7900	26.6100	3.70
1989	4	2	-26.7700	26.6700	3.50
1989	4	27	-26.9100	26.6900	3.60
1989	5	3	-26.7800	26.6200	5.06
1989	7	23	-26.8600	26.7600	4.84
1989	10	7	-26.8900	26.6300	4.84
1989	10	8	-26.9100	26.6500	5.17
1989	10	23	-26.8700	26.7300	3.80
1989	11	4	-26.9000	26.7300	3.50
1989	11	20	-26.9300	26.6400	3.70
1989	11	27	-26.8800	26.5300	3.90
1989	12	2	-26.9000	26.6900	3.60
1990	1	14	-26.9400	26.8300	3.60
1990	1	21	-26.8300	26.7600	3.50
1990	2	7	-26.8300	26.6800	4.74
1990	2	8	-26.8400	26.7500	4.74
1990	2	27	-26.9500	26.6700	4.63
1990	3	3	-26.9500	26.7200	5.28
1990	3	15	-26.8700	26.6400	3.50
1990	3	15	-26.8000	26.7000	4.30
1990	4	26	-26.9300	26.7200	3.20
1990	4	27	-26.7600	26.5500	3.10
1990	5	1	-26.8900	26.7500	3.00
1990	5	6	-26.6600	26.6100	3.40
1990	5	19	-26.9000	26.5900	3.30
1990	5	20	-26.8500	26.7300	3.00
1990	5	20	-26.8100	26.7300	4.52
1990	5	24	-26.8700	26.6300	3.00
1990	5	27	-26.9200	26.8100	3.30
1990	6	11	-26.8700	26.7100	3.00
1990	6	12	-26.8300	26.6400	3.30
1990	7	18	-26.8600	26.6200	4.84
1990	7	27	-26.8000	26.7400	4.30
1990	8	9	-26.9100	26.7500	3.00
1990	9	16	-26.9100	26.7700	3.30
1990	9	22	-26.8700	26.8100	3.10

1990	10	18	-26.9700	26.6000	3.50
1990	10	22	-26.9700	26.6700	3.80
1990	11	15	-26.8300	26.7000	3.70
1990	11	26	-26.7900	26.5600	3.60
1990	12	7	-26.8300	26.5900	3.40
1990	12	24	-26.7800	26.7000	3.80
1990	12	25	-26.8700	26.6000	3.20
1990	12	28	-26.8200	26.8400	3.20
1991	1	3	-26.9000	26.8100	3.00
1991	1	8	-26.8600	26.7000	3.10
1991	2	2	-26.7900	26.4600	3.40
1991	2	3	-26.9200	26.6600	3.10
1991	2	6	-26.8200	26.6300	3.90
1991	2	7	-26.8200	26.8300	3.30
1991	2	15	-26.8800	26.6200	3.20
1991	2	27	-26.8800	26.6700	3.20
1991	2	27	-26.8500	26.8900	3.10
1991	3	1	-26.8300	26.7000	3.20
1991	3	15	-26.8600	26.6400	3.00
1991	3	19	-26.9100	26.6400	3.00
1991	3	21	-26.9700	26.7500	3.40
1991	3	22	-26.8500	26.5900	3.20
1991	4	11	-26.8700	26.7200	3.20
1991	5	2	-26.8300	26.6500	3.30
1991	5	30	-26.8300	26.7000	3.40
1991	5	31	-26.8400	26.6200	3.10
1991	6	5	-26.9200	26.7800	3.00
1991	6	7	-26.8100	26.6200	3.40
1991	6	8	-26.8600	26.7500	3.60
1991	6	10	-26.8700	26.7100	4.95
1991	6	14	-26.8200	26.5900	3.50
1991	6	15	-26.9600	26.8200	3.00
1991	6	24	-26.8500	26.8500	3.40
1991	6	29	-26.7800	26.6600	3.50
1991	7	12	-26.8400	26.5700	4.00
1991	7	17	-26.7100	26.7200	3.80
1991	7	23	-26.7400	26.6800	3.60
1991	7	30	-26.9000	26.8200	3.00
1991	8	1	-26.9000	26.6600	3.10
1991	8	14	-26.9100	26.8300	3.30
1991	8	25	-26.8700	26.7500	3.20
1991	8	31	-26.9400	26.5800	3.30
1991	8	31	-26.7900	26.5500	3.40
1991	9	4	-26.9800	26.8000	3.30
1991	9	10	-26.8200	26.5600	3.50
1991	9	14	-26.9400	26.6900	3.00
1991	9	16	-26.8400	26.7300	3.50
1991	9	30	-26.8600	26.6500	3.50
1991	10	3	-26.8900	26.6400	3.30
1991	10	27	-26.8500	26.7500	3.90
1991	11	3	-26.9400	26.7400	5.28
1991	11	6	-26.8000	26.7200	3.30
1991	11	10	-26.6300	26.5400	3.00
1991	11	22	-26.7900	26.6300	3.50
1991	11	24	-26.8100	26.7000	3.00
1991	12	1	-26.9000	26.7700	5.06
1991	12	1	-26.8500	26.6200	3.10
1991	12	11	-26.8800	26.6300	3.10
1991	12	13	-26.9000	26.6100	3.30
1991	12	15	-26.8700	26.7400	3.60
1991	12	23	-26.9200	26.7700	3.30
1991	12	24	-26.9100	26.7300	3.80
1991	12	24	-26.8700	26.7500	3.20
1992	1	8	-26.8300	26.6800	3.40
1992	1	18	-26.8900	26.7300	4.63
1992	1	18	-26.8800	26.7200	3.30
1992	2	1	-26.8000	26.6500	3.30
1992	2	12	-26.8100	26.6900	3.30
1992	2	12	-26.7100	26.5000	3.10
1992	2	14	-26.8700	26.6100	3.40
1992	2	15	-26.8100	26.7900	3.10
1992	2	17	-26.9700	26.7700	3.20
1992	2	17	-26.7800	26.6400	3.30
1992	2	26	-26.8200	26.5600	3.60
1992	3	2	-26.8700	26.6900	3.00
1992	3	9	-26.8600	26.6900	3.40
1992	3	13	-26.8600	26.6600	3.10
1992	3	29	-26.9000	26.6200	3.00
1992	4	5	-26.9400	26.8400	3.10
1992	4	10	-26.9200	26.7700	3.20
1992	4	13	-26.9100	26.6100	3.50
1992	4	27	-26.8700	26.6700	3.20
1992	4	29	-26.9500	26.7600	3.20
1992	5	1	-26.8800	26.6900	3.60
1992	5	7	-26.8800	26.6900	3.00
1992	5	9	-26.9100	26.7800	3.20
1992	5	9	-26.8300	26.6600	3.20
1992	6	5	-26.8200	26.5300	3.60
1992	6	19	-26.9500	26.6500	4.20
1992	6	22	-26.9800	26.8100	3.10
1992	6	23	-26.9400	26.6100	3.60
1992	6	25	-26.9200	26.7900	3.60
1992	7	3	-26.9200	26.7100	3.00
1992	7	3	-26.8600	26.6800	3.00
1992	7	4	-26.8800	26.6700	3.10

1992	7	5	-26.9100	26.7300	3.00
1992	7	12	-26.7900	26.6100	3.10
1992	7	18	-26.8500	26.7600	3.90
1992	7	19	-26.9000	26.7100	3.00
1992	7	21	-26.9000	26.7300	3.00
1992	7	21	-26.8400	26.8300	3.30
1992	7	25	-26.8400	26.6800	3.50
1992	7	26	-26.7600	26.6800	3.50
1992	7	29	-26.8600	26.7000	3.00
1992	7	29	-26.8200	26.8300	3.10
1992	8	23	-26.9500	26.8700	3.40
1992	8	23	-26.9400	26.8200	3.30
1992	9	1	-26.9000	26.7600	3.80
1992	9	4	-26.8600	26.7900	3.40
1992	9	8	-26.8900	26.8100	3.10
1992	9	23	-26.9400	26.7600	3.00
1992	9	29	-26.8300	26.6400	3.60
1992	10	16	-26.8600	26.7200	3.00
1992	10	21	-26.9200	26.7400	3.10
1992	10	21	-26.8700	26.6900	3.10
1992	10	23	-26.8500	26.7400	3.00
1992	11	8	-26.6300	26.6500	4.71
1992	11	14	-26.9200	26.7300	3.10
1992	11	24	-26.8800	26.8200	3.00
1992	11	28	-27.0000	26.5200	4.84
1992	12	19	-26.9300	26.7200	3.10
1993	1	8	-26.8900	26.7200	3.20
1993	1	14	-26.8900	26.6300	3.10
1993	1	30	-26.8700	26.7000	3.10
1993	1	30	-26.7300	26.6600	3.50
1993	2	9	-26.9000	26.7700	3.00
1993	2	20	-26.9300	26.7000	3.10
1993	2	20	-26.7100	26.6500	3.70
1993	2	22	-26.9200	26.7700	3.30
1993	2	23	-26.8300	26.5300	3.90
1993	2	23	-26.8200	26.6900	4.84
1993	2	24	-26.9000	26.5900	4.74
1993	3	4	-26.8700	26.6700	3.00
1993	3	11	-26.8600	26.7400	3.30
1993	3	19	-26.8900	26.6700	3.10
1993	3	22	-26.7800	26.6100	3.30
1993	3	28	-26.8900	26.7400	3.00
1993	4	14	-26.8500	26.7900	3.10
1993	4	15	-26.9300	26.8000	3.00
1993	4	20	-26.8600	26.8200	3.40
1993	4	28	-26.9100	26.6600	4.41
1993	4	30	-26.8100	26.8100	3.30
1993	5	6	-26.8200	26.7700	3.80
1993	5	11	-26.8500	26.6600	3.20
1993	5	11	-26.8400	26.7000	3.80
1993	5	14	-26.8300	26.7000	3.60
1993	5	19	-26.7900	26.6700	3.30
1993	5	25	-26.8900	26.5700	3.80
1993	5	27	-26.8700	26.7600	3.40
1993	5	28	-26.8900	26.7600	3.00
1993	6	1	-26.8700	26.6600	4.63
1993	6	2	-26.8400	26.6200	3.10
1993	6	5	-26.8900	26.7500	3.10
1993	6	6	-26.8500	26.7300	3.10
1993	6	9	-26.8300	26.6400	3.10
1993	6	10	-26.9300	26.6700	4.41
1993	6	19	-26.9100	26.7500	3.00
1993	6	21	-27.0000	26.7200	3.00
1993	6	28	-27.0100	26.7500	3.40
1993	6	29	-27.0700	26.8200	3.20
1993	7	10	-26.9300	26.8200	3.60
1993	7	22	-26.8500	26.6600	4.30
1993	7	26	-26.8900	26.7300	3.00
1993	7	28	-26.8100	26.7300	3.10
1993	7	30	-26.8500	26.6800	3.10
1993	7	31	-26.8700	26.7500	3.00
1993	8	2	-26.8600	26.6800	3.00
1993	8	7	-26.8800	26.6400	3.50
1993	8	13	-26.7700	26.7100	3.70
1993	8	16	-26.8500	26.7500	3.20
1993	8	18	-26.9000	26.6900	4.84
1993	8	20	-27.0300	26.7300	3.76
1993	8	28	-26.8900	26.5100	3.70
1993	8	31	-26.9000	26.7000	3.40
1993	8	31	-26.8100	26.6400	3.80
1993	9	9	-26.9000	26.7000	3.00
1993	9	18	-26.8600	26.7800	3.60
1993	9	20	-26.9300	26.7000	3.20
1993	9	20	-26.9100	26.6700	3.80
1993	10	5	-26.8900	26.7600	3.20
1993	10	15	-26.8900	26.5300	3.20
1993	10	24	-26.8700	26.6400	3.40
1993	10	24	-26.8500	26.6400	3.00
1993	10	24	-26.7400	26.5300	3.60
1993	10	30	-26.8800	26.6900	4.30
1993	11	2	-26.9100	26.7500	3.40
1993	11	4	-26.8600	26.5900	3.70
1993	11	9	-26.6700	26.6800	3.60
1993	11	19	-26.7400	26.6400	3.80
1993	11	21	-26.9000	26.6900	3.30

1993	12	8	-26.9200	26.7400	3.20
1993	12	9	-26.9000	26.7700	3.50
1993	12	9	-26.8600	26.7400	3.30
1993	12	10	-27.0100	26.7300	4.00
1993	12	10	-26.9600	26.7200	3.30
1993	12	13	-26.9400	26.7900	3.60
1993	12	13	-26.8900	26.8100	3.10
1993	12	15	-27.0000	26.7500	3.90
1993	12	20	-26.9200	26.7200	4.84
1993	12	20	-26.9100	26.7100	4.95
1993	12	22	-26.7900	26.7600	3.20
1993	12	27	-26.8100	26.6300	3.70
1994	1	4	-26.8500	26.7000	3.00
1994	1	4	-26.8300	26.6900	4.63
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1994	1	15	-26.9200	26.6200	3.50
1994	1	15	-26.8800	26.9600	3.00
1994	1	24	-26.7800	26.7900	3.20
1994	1	26	-26.6100	27.2000	3.30
1994	2	3	-26.8900	26.6800	3.00
1994	2	3	-26.8700	26.8000	3.10
1994	2	15	-26.9100	26.6700	3.60
1994	2	17	-26.9300	26.7000	3.30
1994	2	25	-26.8200	26.6500	3.20
1994	3	13	-26.9500	26.8200	3.30
1994	4	1	-26.9000	26.6800	4.74
1994	4	13	-26.8200	26.7000	3.10
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1994	4	23	-26.9000	26.7300	3.30
1994	5	10	-26.8900	26.7600	4.95
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1994	5	30	-26.8400	26.7800	3.00
1994	6	4	-26.8400	26.7300	3.10
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1994	6	12	-26.9400	26.7600	3.10
1994	6	13	-26.8900	26.7100	3.00
1994	6	16	-26.8800	26.6400	3.30
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1994	6	18	-26.9200	26.8500	3.00
1994	6	23	-26.8900	26.6900	3.30
1994	6	30	-26.8900	26.7500	3.00
1994	7	7	-26.8800	26.7500	3.10
1994	7	27	-26.8700	26.7700	4.20
1994	7	31	-26.9000	26.8200	3.10
1994	7	31	-26.8600	26.6500	4.30
1994	8	2	-26.9000	26.7100	3.40
1994	8	26	-26.9100	26.7300	3.00
1994	9	6	-26.8000	26.7200	3.80
1994	9	21	-26.9200	26.7400	3.40
1994	9	21	-26.8700	26.7200	3.10
1994	10	9	-26.9000	26.7800	3.60
1994	10	12	-26.8800	26.8000	3.10
1994	10	13	-26.9500	26.7300	4.41
1994	10	18	-26.9500	26.7400	3.10
1994	10	28	-26.8900	26.8500	3.00
1994	10	28	-26.8600	26.6800	3.10
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1994	11	28	-26.8900	26.6900	3.00
1994	11	28	-26.8500	26.7200	3.60
1994	11	30	-26.8600	26.7100	4.10
1994	12	7	-26.9000	26.6300	3.20
1994	12	7	-26.8900	26.7000	3.10
1994	12	29	-26.9400	26.6500	3.10
1994	12	30	-27.0000	26.8100	3.20
1994	12	30	-26.9900	26.7200	3.10
1995	1	23	-26.8100	26.5000	3.30
1995	2	1	-26.9200	26.8200	3.50
1995	2	2	-26.9300	26.6900	3.80
1995	2	10	-26.8300	26.6700	5.17
1995	2	18	-26.9000	26.7200	3.20
1995	3	2	-26.9200	26.7200	3.40
1995	3	18	-26.8400	26.6900	3.00
1995	3	30	-26.9600	26.7700	3.30
1995	3	31	-26.9400	26.7800	3.30
1995	4	2	-26.7800	26.6500	3.30
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1995	4	25	-26.9100	26.7300	3.00
1995	5	7	-26.9200	26.6500	3.00
1995	5	16	-26.9700	26.6800	3.20
1995	5	18	-26.9200	26.7800	3.10
1995	5	20	-26.9200	26.6700	4.63
1995	5	31	-26.9400	26.7600	3.50
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1995	6	6	-26.8900	26.7500	3.10
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1995	6	18	-26.9200	26.7900	3.30
1995	6	19	-26.9300	26.8100	3.00
1995	6	23	-26.9400	26.7700	3.20
1995	7	5	-26.9000	26.6800	3.00

1995	7	24	-26.8700	26.7100	3.10
1995	7	30	-26.8700	26.6800	3.00
1995	7	31	-26.9000	26.6900	3.10
1995	7	31	-26.8900	26.7800	3.10
1995	8	2	-26.9000	26.7400	3.00
1995	8	3	-26.9400	26.7500	3.40
1995	8	3	-26.8800	26.7500	3.70
1995	8	19	-26.8900	26.7600	3.30
1995	8	23	-26.9400	26.7300	3.20
1995	9	3	-26.8600	26.6600	4.63
1995	9	20	-26.8600	26.7300	3.20
1995	9	24	-26.8400	26.6700	4.52
1995	9	25	-26.8900	26.6800	3.20
1995	10	11	-26.9500	26.7000	3.30
1995	10	27	-26.9400	26.7400	3.00
1995	11	10	-26.9200	26.6200	4.30
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1995	11	15	-26.9100	26.7000	3.00
1995	11	15	-26.8800	26.6900	3.40
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1995	11	25	-26.9000	26.5900	3.10
1995	11	29	-26.8800	26.7800	3.10
1995	11	30	-26.9100	26.6900	3.20
1995	12	7	-26.9100	26.7000	3.00
1995	12	9	-26.9300	26.6600	3.00
1995	12	24	-26.9300	26.6600	3.10
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1996	3	2	-26.9200	26.6000	3.80
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1996	4	3	-26.9000	26.7100	3.20
1996	4	4	-26.9000	26.6800	3.40
1996	4	5	-26.9200	26.7100	4.52
1996	4	5	-26.9000	26.7200	3.60
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1996	5	14	-26.8800	26.6600	3.10
1996	5	17	-26.8800	26.6200	3.20
1996	5	19	-26.9200	26.7200	3.60
1996	6	5	-26.9400	26.7700	3.00
1996	6	7	-26.9400	26.6900	3.20
1996	6	16	-26.8900	26.6600	4.41
1996	6	29	-26.9600	26.8100	4.63
1996	7	2	-26.9000	26.6600	3.40
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1996	7	30	-26.6400	26.6800	3.60
1996	8	15	-26.8500	26.6300	3.00
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1996	9	7	-26.8900	26.6500	4.52
1996	9	10	-26.8100	26.7000	3.10
1996	9	16	-26.8800	26.8000	3.80
1996	9	16	-26.8500	26.7200	4.74
1996	9	18	-26.8800	26.7600	3.20
1996	9	24	-26.8400	26.7300	3.00
1996	9	30	-26.9300	26.8100	3.00
1996	10	1	-26.7000	26.7100	4.30
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1996	10	15	-27.1200	26.7600	3.10
1996	10	16	-26.8900	26.6000	3.30
1996	10	17	-27.1100	26.7600	3.20
1996	10	23	-26.8200	26.6100	4.00
1996	10	28	-26.9500	26.7600	3.20
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1996	11	1	-26.8300	26.7400	3.00
1996	11	7	-27.0300	26.5400	4.63
1996	11	9	-26.8400	26.8100	3.00
1996	11	14	-26.9200	26.8300	3.20
1996	11	15	-26.8400	26.7000	3.50
1996	11	18	-27.1000	26.7700	3.70
1996	11	28	-26.9500	26.6300	3.70
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1996	12	18	-26.8900	26.7700	3.70
1996	12	25	-26.9300	26.6200	4.41
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1997	1	4	-26.9500	26.6800	3.00
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1997	1	10	-26.9500	26.7900	3.30
1997	1	10	-26.9000	26.8000	3.10
1997	1	11	-26.8400	26.7000	3.60
1997	1	13	-26.8200	26.7100	3.00
1997	1	14	-27.1000	26.7100	3.80

1997	1	20	-26.9800	26.7600	4.00
1997	1	20	-26.8500	26.7200	3.50
1997	1	23	-26.7900	26.7300	3.20
1997	1	28	-26.8400	26.7300	3.00
1997	1	31	-27.1000	26.5500	3.60
1997	2	1	-26.8100	26.7300	3.10
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1997	2	10	-26.9300	26.7600	5.14
1997	2	11	-26.8700	26.8200	3.40
1997	2	15	-26.9200	26.8700	3.00
1997	2	15	-26.8800	26.7500	3.20
1997	2	21	-26.8300	26.7600	3.80
1997	2	22	-26.8600	26.7200	3.40
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1997	4	13	-26.7800	26.8500	3.00
1997	4	27	-26.8000	26.7800	3.60
1997	5	5	-26.8700	26.8000	3.40
1997	5	7	-26.9200	26.8300	3.40
1997	5	9	-27.1100	26.8200	3.00
1997	5	21	-26.8800	26.7000	3.80
1997	5	21	-26.8100	26.7300	3.30
1997	5	23	-26.9200	26.7700	4.41
1997	5	23	-26.8500	26.7100	3.40
1997	5	25	-26.8400	26.7400	3.00
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1997	6	5	-26.9300	26.9100	3.20
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1997	6	11	-26.7300	26.8200	3.00
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1997	6	19	-26.8800	26.7900	3.70
1997	6	25	-26.8800	26.5400	3.60
1997	7	1	-26.7500	26.8700	3.00
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1997	7	4	-26.7400	26.8200	3.70
1997	7	9	-26.9400	26.7300	3.40
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1997	7	17	-26.8700	26.7600	3.70
1997	7	18	-26.9600	26.8200	3.50
1997	7	21	-26.8700	26.7800	4.95
1997	7	22	-26.9300	26.8100	3.20
1997	7	25	-27.0300	26.7300	3.50
1997	7	29	-26.9300	26.8500	3.00
1997	8	11	-26.9400	26.8800	3.00
1997	8	17	-26.7800	26.6600	3.00
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1997	8	18	-27.0000	26.7200	3.30
1997	8	21	-27.0400	26.9200	3.40
1997	8	31	-26.9700	26.7500	3.00
1997	9	13	-26.8600	26.6300	4.00
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1997	9	30	-26.9300	26.6300	3.90
1997	10	3	-26.8700	26.6600	3.00
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1997	10	11	-26.8500	26.6300	4.19
1997	10	17	-26.8800	26.7000	3.00
1997	10	20	-26.9000	26.8000	4.09
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1997	10	29	-26.9700	26.7400	3.40
1997	11	10	-26.9600	26.7500	3.10
1997	11	22	-26.8500	26.6900	3.20
1997	11	30	-26.9100	26.9300	3.10
1997	11	30	-26.8800	26.9100	3.20
1997	12	11	-26.9300	26.7800	3.60
1997	12	11	-26.9200	26.7000	3.20
1997	12	11	-26.9100	26.6800	4.74
1997	12	11	-26.9000	26.8200	3.20
1997	12	12	-26.9500	26.7000	4.74
1997	12	16	-26.8700	26.7700	3.30
1998	1	6	-26.9200	26.8600	3.50
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1998	1	15	-26.8600	26.7800	3.70
1998	1	15	-26.7000	26.8000	4.09
1998	1	16	-27.0000	27.0100	3.20
1998	1	17	-26.8300	26.7500	4.52
1998	1	22	-26.9100	27.0000	3.20
1998	2	6	-27.0000	26.9700	3.60
1998	2	6	-26.9400	26.6900	3.80
1998	2	7	-26.9300	26.8100	3.30
1998	2	11	-26.9400	26.7300	3.10
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1998	2	18	-26.9100	26.5800	4.52
1998	2	21	-26.9100	26.6800	3.20
1998	2	21	-26.9100	26.8400	3.10
1998	2	22	-26.8500	26.7100	3.00
1998	2	23	-27.0300	26.9300	3.20
1998	3	5	-27.0900	26.7500	3.40

1998	3	5	-26.9700	26.8100	4.52
1998	3	7	-26.8900	26.6000	3.00
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1998	3	12	-26.8900	26.8200	3.50
1998	3	14	-26.9600	26.8600	3.10
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1998	3	20	-27.0600	26.8400	3.00
1998	3	23	-26.9000	26.7100	3.10
1998	3	24	-26.8500	26.8100	3.70
1998	3	25	-26.8500	26.7100	3.80
1998	3	31	-26.7800	26.7600	3.30
1998	4	3	-26.8900	26.8700	3.00
1998	4	6	-26.8800	26.7900	3.70
1998	4	10	-27.0100	26.8000	3.00
1998	4	14	-26.9100	26.8000	3.30
1998	4	21	-26.9800	26.8300	3.40
1998	4	21	-26.8900	26.8100	3.10
1998	4	24	-26.9700	26.7900	3.20
1998	5	2	-26.8700	26.6900	3.30
1998	5	9	-27.0100	26.6800	3.30
1998	5	11	-26.9200	26.8400	3.00
1998	5	17	-26.9700	26.9000	4.19
1998	5	21	-26.9100	26.6800	3.10
1998	5	21	-26.9000	26.7400	3.20
1998	5	26	-26.9000	26.7500	3.20
1998	6	5	-26.8600	26.6800	3.00
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1998	6	19	-26.8800	26.7900	3.20
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1998	7	2	-26.9700	26.8100	3.20
1998	7	6	-26.9700	26.7700	3.70
1998	7	6	-26.8300	26.6900	3.00
1998	7	7	-26.9100	26.8400	3.10
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1998	7	17	-26.9300	26.5800	3.30
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1998	7	22	-26.9300	26.7900	3.40
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1998	8	8	-26.8900	26.8300	3.20
1998	8	9	-26.9900	26.7700	3.80
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1998	8	21	-26.9400	26.7200	3.20
1998	8	26	-26.8100	26.8600	3.70
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1998	9	19	-26.8500	26.6800	3.70
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1998	9	25	-26.8900	26.7100	4.63
1998	9	25	-26.8200	26.6400	3.00
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1998	10	3	-26.9000	26.6800	3.70
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1998	10	28	-26.9600	26.8500	3.20
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1998	11	16	-26.9200	26.7200	3.50
1998	11	17	-26.8700	26.6800	4.74
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1998	11	18	-26.9000	26.7200	3.00
1998	11	20	-26.9200	26.8500	3.30
1998	11	25	-26.9100	26.7200	3.20
1998	11	26	-26.9500	26.6900	3.50
1998	12	1	-26.9100	26.7100	3.60
1998	12	7	-26.8500	26.7000	3.40
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1998	12	15	-26.9400	26.7200	3.80
1998	12	16	-26.7800	26.8800	3.30
1998	12	27	-26.8800	26.6700	3.50
1999	1	7	-26.9400	26.6100	4.19
1999	1	11	-26.9100	26.6900	3.30
1999	1	19	-27.0100	26.7100	4.30
1999	1	23	-26.9700	26.7400	3.20
1999	1	23	-26.9200	26.6300	4.41
1999	1	24	-26.9600	27.0100	3.10
1999	1	28	-26.8800	26.6400	3.10
1999	2	1	-26.9600	26.8100	3.00
1999	2	8	-26.8300	26.7000	3.00
1999	2	24	-26.8100	26.7800	3.10
1999	3	25	-26.8800	26.7100	3.10
1999	3	26	-27.0100	26.7900	3.00
1999	4	5	-27.0000	26.9000	3.40
1999	4	15	-26.8600	26.7000	3.30
1999	4	17	-26.8500	26.6900	3.10
1999	4	20	-26.8800	26.8200	3.00
1999	4	22	-27.0300	26.7900	3.20
1999	4	25	-26.8400	26.7000	3.00
1999	4	29	-26.9000	26.8200	3.20
1999	5	10	-26.7900	26.7000	4.41
1999	5	28	-26.8600	26.8100	3.60

1999	6	5	-26.8000	26.8000	3.20
1999	6	24	-26.8400	26.7100	3.60
1999	7	3	-26.8700	26.6800	3.40
1999	7	10	-26.7900	26.8000	3.80
1999	7	10	-26.7700	26.8600	3.30
1999	7	14	-26.9300	26.7300	3.10
1999	7	18	-26.9500	26.8900	4.41
1999	7	19	-26.7900	26.8500	3.40
1999	7	30	-26.8000	26.6300	3.20
1999	8	1	-26.8100	26.7700	3.20
1999	8	3	-26.8100	26.5700	3.10
1999	8	20	-26.9800	26.6200	3.70
1999	8	25	-26.9100	26.7900	3.20
1999	8	29	-26.9000	27.0800	3.00
1999	9	4	-26.8000	26.7300	3.60
1999	9	6	-26.9500	26.8300	4.00
1999	9	10	-26.9300	26.8200	3.00
1999	9	14	-26.8900	26.7500	3.50
1999	9	14	-26.8400	26.7600	4.52
1999	9	17	-26.9300	26.8400	3.50
1999	9	29	-26.8400	26.7100	3.80
1999	10	4	-26.9600	26.8600	3.40
1999	10	5	-26.9700	26.9100	3.30
1999	10	11	-26.9300	26.8000	4.52
1999	10	11	-26.8800	26.6300	3.50
1999	10	11	-26.8600	26.7200	3.40
1999	10	12	-26.9000	26.7600	3.30
1999	10	12	-26.8500	26.8100	4.19
1999	10	18	-26.8900	26.7700	3.00
1999	10	18	-26.8300	26.7700	3.70
1999	10	25	-26.7600	26.7900	3.70
1999	10	26	-26.8700	26.7400	3.70
1999	10	26	-26.7900	26.6600	3.30
1999	10	28	-26.9000	26.8200	3.00
1999	10	28	-26.7900	26.7700	3.10
1999	11	12	-26.9100	27.0600	3.00
1999	11	23	-26.9400	26.7000	3.30
1999	11	25	-26.8700	27.1100	3.10
1999	12	15	-26.9400	27.0200	3.20
1999	12	25	-26.7600	26.7600	3.10
2000	1	5	-26.8400	26.8300	3.20
2000	1	9	-26.8700	26.8700	3.30
2000	1	12	-26.8800	26.9300	3.20
2000	1	13	-26.8500	26.8600	3.30
2000	1	14	-26.8400	26.7600	3.00
2000	1	26	-26.9400	27.0800	4.22
2000	1	26	-26.8300	26.9900	4.09
2000	2	9	-26.8100	27.0800	3.60
2000	2	21	-26.9100	27.0100	3.10
2000	2	25	-26.8800	26.8300	3.10
2000	3	22	-27.2100	26.5800	3.00
2000	3	23	-26.9700	26.7700	3.10
2000	3	24	-26.9100	26.6600	3.10
2000	3	26	-26.9400	26.7600	3.20
2000	3	27	-26.8600	26.7300	3.00
2000	3	31	-26.8700	26.7300	3.10
2000	4	1	-26.9400	26.6700	3.20
2000	4	1	-26.8100	26.7300	3.00
2000	4	7	-26.8500	26.8300	4.41
2000	4	8	-26.7600	26.8200	3.00
2000	4	21	-26.7900	26.7700	3.20
2000	4	25	-26.8900	26.8300	3.10
2000	4	29	-26.8800	26.8300	4.00
2000	4	29	-26.7100	26.6100	4.53
2000	5	18	-27.1200	27.0000	4.41
2000	5	19	-26.8100	26.6300	3.40
2000	5	26	-26.9300	26.7200	3.00
2000	6	4	-26.8400	26.7100	3.10
2000	6	8	-26.7900	26.8100	3.00
2000	6	14	-26.9400	26.7700	3.10
2000	6	14	-26.8900	26.7000	3.20
2000	6	19	-26.9500	26.7700	3.60
2000	6	20	-27.0000	26.7700	4.09
2000	6	25	-26.9700	26.7500	3.10
2000	6	25	-26.8900	26.7600	4.41
2000	6	26	-26.8800	26.8300	3.30
2000	7	1	-26.9600	26.6600	3.80
2000	7	4	-26.9400	26.9800	3.20
2000	7	6	-26.9400	27.2300	3.98
2000	7	11	-26.8900	26.7400	3.20
2000	7	28	-26.9600	26.7500	4.30
2000	8	6	-26.9300	26.8000	4.09
2000	8	6	-26.9100	26.7500	3.70
2000	8	10	-26.7900	26.7100	4.09
2000	8	13	-26.8600	26.7800	3.30
2000	8	16	-26.8700	26.7700	3.00
2000	8	29	-26.7500	26.8900	3.00
2000	9	17	-26.9400	26.7200	4.41
2000	9	20	-26.8300	26.7100	3.20
2000	9	24	-26.8300	26.7100	4.30
2000	9	28	-26.8200	26.7700	3.20
2000	9	29	-26.8300	26.7600	3.10
2000	10	25	-26.9500	27.0200	3.20
2000	10	29	-26.8800	26.8400	3.30
2000	11	7	-26.6300	26.7200	3.20

2000	11	14	-26.9800	26.8200	3.40
2000	11	24	-26.8500	26.8300	4.52
2000	12	1	-26.7500	26.8300	3.70
2000	12	5	-26.8800	27.2100	4.19
2000	12	9	-26.9500	26.8100	3.40
2000	12	10	-26.8800	26.7100	3.00
2000	12	16	-26.8900	26.7200	3.60
2001	1	24	-26.7400	26.8400	5.06
2001	1	25	-26.9300	26.7300	4.63
2001	1	25	-26.9000	26.6700	3.50
2001	2	7	-26.9100	26.7900	3.20
2001	2	8	-26.8600	26.7900	3.60
2001	2	12	-27.0100	26.7400	3.00
2001	2	16	-26.8500	26.5800	3.40
2001	2	21	-26.9700	26.8500	4.52
2001	2	25	-26.9100	26.7900	3.30
2001	3	1	-26.8400	26.7500	3.20
2001	3	2	-26.9200	26.7700	3.30
2001	3	2	-26.9000	26.7500	3.30
2001	3	4	-26.8700	26.7500	3.30
2001	3	4	-26.7700	26.6400	3.00
2001	3	6	-26.8300	26.7100	3.40
2001	3	31	-26.9600	26.8000	4.41
2001	4	21	-26.8500	26.7900	3.60
2001	6	13	-26.9300	26.7700	4.30
2001	6	14	-26.9700	26.7100	4.19
2001	7	4	-26.8700	26.7500	4.41
2001	7	4	-26.8300	26.7400	3.80
2001	7	28	-26.8700	26.7800	3.80
2001	7	31	-26.9400	26.7900	4.77
2001	8	8	-26.9100	26.6800	3.50
2001	8	14	-26.8500	26.8000	4.19
2001	9	17	-26.8800	26.8800	3.60
2001	9	20	-26.9700	26.8300	4.30
2001	9	24	-26.8900	26.7700	3.50
2001	10	4	-26.8800	26.6700	3.60
2001	10	13	-26.9000	26.7600	3.70
2001	10	30	-26.8800	26.8000	3.98
2001	11	24	-26.8600	26.9000	4.52
2001	12	2	-26.8600	26.7900	3.80
2002	1	31	-26.7900	26.5700	4.41
2002	2	20	-26.8300	26.6800	3.50
2002	2	23	-26.9200	26.7000	4.52
2002	3	23	-26.8300	26.6600	4.53
2002	3	30	-26.7200	26.6300	4.63
2002	5	27	-26.9900	26.7000	5.06
2002	5	28	-26.9300	27.1000	5.06
2002	6	17	-26.9100	26.6800	4.41
2002	7	26	-27.0000	26.8000	4.41
2002	8	1	-26.9100	26.7300	3.60
2002	8	20	-26.8800	26.8100	3.50
2002	11	28	-26.9300	26.6700	3.60
2002	12	10	-26.8700	26.7900	5.17
2002	12	20	-26.7900	26.8100	4.19
2003	3	16	-27.1500	26.8600	3.80
2003	4	19	-26.9400	26.7400	3.33
2003	5	6	-26.8300	26.7500	3.70
2003	5	22	-26.9900	26.7400	3.70
2003	6	20	-26.8200	26.8400	3.90
2003	8	14	-26.8800	26.7400	4.00
2003	9	5	-26.9300	26.6900	3.60
2003	11	27	-26.9300	26.8200	4.00
2004	1	13	-26.9500	26.8400	4.00
2004	3	23	-26.9700	26.7500	4.52
2004	7	2	-27.0000	26.8000	3.80
2004	8	3	-26.9500	26.6800	4.52
2004	8	18	-27.0100	26.7200	3.50
2004	9	6	-26.8900	26.5200	4.83
2004	9	18	-26.8300	26.7500	3.50
2004	9	22	-26.9500	26.7700	3.50
2004	10	21	-26.9300	26.8400	3.60
2004	11	20	-26.7900	26.8100	3.70
2004	12	22	-27.0300	26.7500	3.70
2004	12	22	-26.8900	26.8100	3.60
2005	1	25	-26.9300	26.6500	4.19
2005	1	28	-26.9600	26.7800	3.50
2005	1	29	-26.9600	26.7500	3.80
2005	2	17	-26.9700	26.7100	4.19
2005	3	9	-26.8900	26.7400	5.30
2005	3	9	-26.8600	26.8000	4.52
2005	4	1	-27.0000	26.7900	3.60
2005	4	2	-27.0100	26.7700	3.70
2005	4	13	-26.8700	26.7800	4.00
2005	4	13	-26.8700	26.8400	4.10
2005	5	8	-26.8900	26.8600	3.50
2005	7	14	-26.9200	26.7600	3.50
2005	8	25	-26.9000	26.7500	3.70
2005	8	28	-26.9800	26.8000	3.50
2005	8	30	-26.8900	26.7000	4.09
2005	10	11	-26.9200	26.7400	3.50
2005	10	12	-27.0900	26.7500	4.96
2005	10	12	-26.9700	26.6800	4.50
2005	10	13	-26.9900	26.7800	3.50
2005	10	13	-26.9800	26.7100	3.70
2005	10	24	-26.9700	26.7700	3.70

2005	12	27	-26.9200	26.8200	3.70
2006	1	29	-26.9300	26.7600	4.19
2006	3	19	-26.9500	26.7000	4.20
2006	3	23	-26.9400	26.6600	3.60
2006	4	15	-26.9700	26.7900	3.80
2006	4	18	-26.9000	26.8100	3.70
2006	4	29	-27.0100	26.6800	4.74
2006	5	12	-26.9200	26.8100	3.80
2006	5	24	-26.9700	26.8000	3.60
2006	6	26	-26.9200	26.7100	4.19
2006	7	7	-26.9400	26.8100	3.98
2006	7	13	-26.9900	26.7000	3.70
2006	8	8	-27.0300	26.8100	4.19
2006	10	12	-26.9100	26.7700	4.41
2006	11	29	-26.9400	26.7200	3.60
2007	2	5	-26.9800	26.7400	4.52
2007	4	10	-26.9000	26.7600	4.30
2007	4	23	-26.9900	26.7500	3.98
2007	7	28	-26.8600	26.8300	3.50
2007	9	3	-26.9100	26.8000	3.50
2007	12	28	-26.9200	26.7900	4.52
2008	2	15	-26.8500	26.7500	3.60
2008	4	3	-26.9700	26.7900	3.50
2008	5	30	-26.8200	26.7800	3.60
2008	6	13	-27.0000	26.7700	3.20
2008	7	7	-27.0300	26.7300	3.90
2008	11	23	-26.9400	26.7500	4.41
2008	12	15	-26.9700	26.7500	4.19
2009	1	17	-27.0100	26.8000	3.50
2009	3	13	-26.9100	26.8100	4.41
2009	3	16	-26.9400	26.7400	4.95
2009	4	18	-26.9000	26.7400	4.41
2009	6	5	-26.8700	26.8000	3.50
2009	11	9	-27.0100	26.5600	3.10
2009	11	29	-26.9300	26.7600	4.74
2010	2	15	-26.9400	26.7400	4.63
2010	3	21	-26.8700	26.7700	4.77
2010	6	7	-26.9600	26.8300	4.52
2010	6	19	-26.8900	26.6900	3.70
2010	8	16	-26.9900	26.7100	3.10
2010	8	28	-26.9000	26.8300	3.10
2010	11	9	-26.9200	26.7900	3.10
2011	3	9	-26.8800	26.6600	4.63
2011	4	30	-27.0200	26.7700	3.50
2011	11	26	-26.8600	26.6700	3.70
2011	12	13	-26.9200	26.8000	3.60
2011	12	27	-26.9200	26.7800	4.52
2011	12	28	-26.9000	26.8900	4.84
2012	1	5	-26.9200	26.8300	3.60
2012	3	8	-26.8900	26.7100	4.10
2012	3	14	-26.9100	26.7700	4.30
2012	5	23	-26.9700	26.8000	4.19
2012	11	1	-26.8700	26.6300	3.30
2013	1	14	-26.9600	26.6700	3.10
2013	7	13	-26.9200	26.7370	4.40
2014	6	15	-26.9892	26.7614	4.90
2014	8	5	-26.9899	26.7048	5.40
2014	8	5	-26.9113	26.7818	4.30
2014	8	5	-26.8398	26.7209	4.40
2014	8	7	-26.8230	26.6513	4.60
2014	8	8	-26.9249	26.7302	4.60
2014	8	27	-26.9927	26.7594	4.60
2014	8	30	-26.9133	26.8688	4.70
2014	10	28	-26.9704	26.8350	4.50
2015	2	6	-26.9636	27.0879	4.30

Appendix B

Results of seismic hazard analysis for the area in vicinity of the KTD in terms of seismic event magnitude (tabulated values of mean activity rate, return periods and probability of exceedance in 1, 5, 10 and 25 years).

```
=====================================================================
 File       : info_PSHA_MAG_KTD.txt
 Created on : 06-Aug-2016 00:10:16
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 SEISMIC HAZARD ASSESSMENT FOR SELECTED AREA
 FROM PRE-HISTORIC, HISTORIC and INCOMPLETE DATA
 ORIGIN TIME OF PRE-HISTORIC EVENTS CAN BE UNCERTAIN

 FLOW OF SEISMIC EVENTS IS MODELED BY BAYESIAN (COMPOUND) DISTRIBUTIONS
 WHICH ARE TAKING INTO ACCOUNT UNCERTAINTY OF SEISMIC HAZARD MODEL

 HAZARD PARAMETERS BEATA AND LAMBDA ARE CALCULATED SIMULTANEOUSLY
 MAGNITUDE ERRORS ARE DISTRIBUTED NORMALLY
 RANGE OF MAGNITUDE INTEGRATION : < m_min, m_max >

 REGONAL MAXIMUM MAGNITUDE CAN BE ESTIMATED ACCORDING TO :

     (1) Classic Maximum Likelihood Procedure
     (2) Gibowicz-Kijko (1994)
     (3) Gibowicz-Kijko-Bayes
     (4) Kijko-Sellevoll (1989)
     (5) Kijko-Sellevoll-Bayes
     (6) Tate-Pisarenko
     (7) Tate-Pisarenko-Bayes
     (8) Non-Parametric (Gaussian) procedure

 Theory of the HAZARD evaluation procedure is given in papers:

    "Estimation of earthquake hazard parameters
     from Incomplete data files", Part II.
     by A.Kijko and M.A. Sellevoll (1992)
     Bull. Seism. Soc. Am. vol.82, p.120-134.

    "Estimation of the Maximum Earthquake Magnitude"
     by A.Kijko (2004). Pure App. Geophys., vol.161, p.1655-1681.

  and

    "Statistical tools for maximum possible
     earthquake magnitude estimation"
     by A. Kijko and M. Singh (2011).
     Acta Geophysica, vol.59, p.674-700.

=====================================================================
 PROGRAM NAME     : HA3 (H = Hazard; A = Area)

 WRITTEN          : 15 AUG 1999 by A.Kijko

 REVISION 1       : 21 MAR 2005 by A.Kijko
 REVISION 2       : 25 JUL 2005 by J.Ramperthap
 REVISION 3       : 15 AUG 2005 by J.Ramperthap
 REVISION 4       : 22 JUN 2006 by A.Kijko
 REVISION 5       : 08 JUN 2010 by A.Kijko (ver 3.00 beta)
 REVISION 6       : 08 Nov 2013 by A.Kijko (ver 3.01)
```

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

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 University of Pretoria,
 Pretoria 0002, South Africa.
 E-mail : andrzej.kijko@up.ac.za

======================================================================
```

NAME OF THE AREA: KTD

```
                      HISTORIC DATA:
                   ********************

 NAME OF HISTORIC DATA FILE: e.txt

 BEGINING OF HISTORIC DATA (Y-M-D) = 1966 5 1
 END      OF HISTORIC DATA (Y-M-D) = 1971 4 30
 NUMBER OF HISTORIC EQ-s           = 5
 "THRESHOLD" MAG. OF HISTORIC EQ-s = 3.5
 STANDARD ERROR OF EQ-e MAGNITUDE  = 0.25

 1966   7  25  3.8
 1968   2   8  3.8
 1968   5   3  4.1
 1969   5  15  4.3
 1970   5  23  5.1

 LARGEST EQ IN HISTORIC CATALOG = 5.1

                  COMPLETE DATA:
               ********************

 NAME OF COMPLETE DATA FILE #1: c_35_mod.txt

 BEGINING OF COMPLETE DATA #1: 1971 5 1
 END      OF COMPLETE DATA #1: 2015 2 7
 LEVEL OF COMPLETENESS                = 3.5
 NUMBER OF EQ-s                       = 591
 STANDARD ERROR OF EQ-e MAGNITUDE     = 0.15
 LARGEST EQ IN COMPLETE CATALOG #1    = 5.4

 PROVISION FOR INDUCED SEISMICITY : NOT REQUIRED
 ===============================================

                        ***

 TIME SPAN OF WHOLE CATALOG           = 48.77 [Y]
 MAXIMUM MAGNITUDE IN THE CATALOG     = 5.4
 SE OF MAXIMUM OBSERVED MAGNITUDE     = 0.1
 MODEL UNCERTAINTY OF BETA            = 25 [per cent]
 MODEL UNCERTAINTY OF LAMBDA          = 25 [per cent]

 CALCULATIONS ARE PERFORMED FOR MINIMUM MAGNITUDE Mmin = 3.50

 PRIOR VALUE OF PARAMETER b           = 1.25
 SD OF PRIOR b-VALUE                  = 0.1
```

RESULTS
****

BETA   = 2.04 +- 0.10 (b = 0.89 +- 0.04)
LAMBDA = 9.320 +- 1.677 (for Mmin = 3.50)
Mmax   = 5.63 +- 0.11 (for Mmax obs. = 5.40 +- 0.10)

```
 Maximum Regional Magnitude Mmax is calculated
 according to procedure by Kijko-Sellevoll-Bayes

 COV(Beta,Lambda) = -0.048
```

Mag	Lambda	RP [Y]	Prob(T = 1y	5y	10y	25y)
3.5	9.3199e+000	1.07e-001	0.99935	1.00000	1.00000	1.00000
3.6	7.5735e+000	1.32e-001	0.99797	1.00000	1.00000	1.00000
3.7	6.1635e+000	1.62e-001	0.99456	1.00000	1.00000	1.00000
3.8	5.0220e+000	1.99e-001	0.98732	1.00000	1.00000	1.00000
3.9	4.0954e+000	2.44e-001	0.97392	1.00000	1.00000	1.00000
4.0	3.3415e+000	2.99e-001	0.95191	0.99999	1.00000	1.00000
4.1	2.7264e+000	3.67e-001	0.91934	0.99995	1.00000	1.00000
4.2	2.2235e+000	4.50e-001	0.87532	0.99978	1.00000	1.00000
4.3	1.8113e+000	5.52e-001	0.82020	0.99924	0.99999	1.00000
4.4	1.4727e+000	6.79e-001	0.75556	0.99766	0.99997	1.00000
4.5	1.1938e+000	8.38e-001	0.68380	0.99374	0.99987	1.00000
4.6	9.6374e-001	1.04e+000	0.60774	0.98519	0.99947	1.00000
4.7	7.7347e-001	1.29e+000	0.53015	0.96869	0.99818	1.00000
4.8	6.1578e-001	1.62e+000	0.45350	0.94015	0.99454	0.99998
4.9	4.8484e-001	2.06e+000	0.37976	0.89536	0.98552	0.99988
5.0	3.7589e-001	2.66e+000	0.31033	0.83086	0.96583	0.99938
5.1	2.8506e-001	3.51e+000	0.24614	0.74471	0.92744	0.99724
5.2	2.0918e-001	4.78e+000	0.18765	0.63692	0.85998	0.98916
5.3	1.4568e-001	6.86e+000	0.13500	0.50949	0.75198	0.96242
5.4	9.2440e-002	1.08e+001	0.08805	0.36596	0.59289	0.88451
5.5	4.7719e-002	2.10e+001	0.04653	0.21088	0.37513	0.68355
5.6	1.0088e-002	9.91e+001	0.01003	0.04912	0.09568	0.22139

Appendix C

Attenuation of Vertical Peak Acceleration

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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.

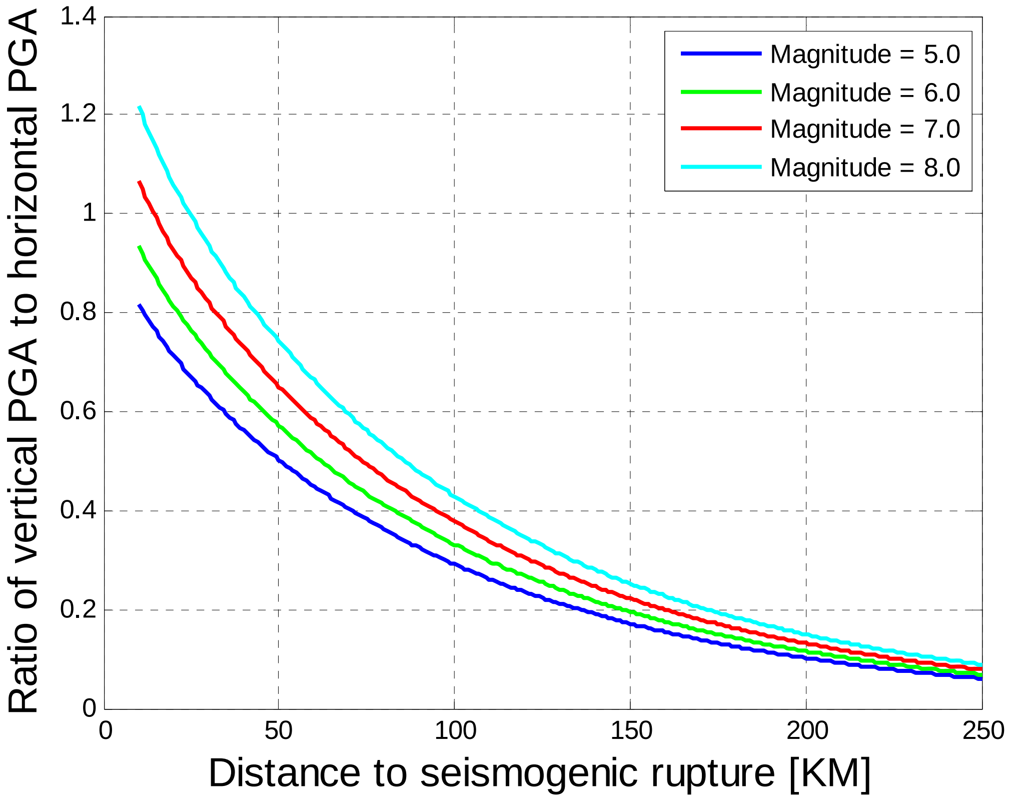
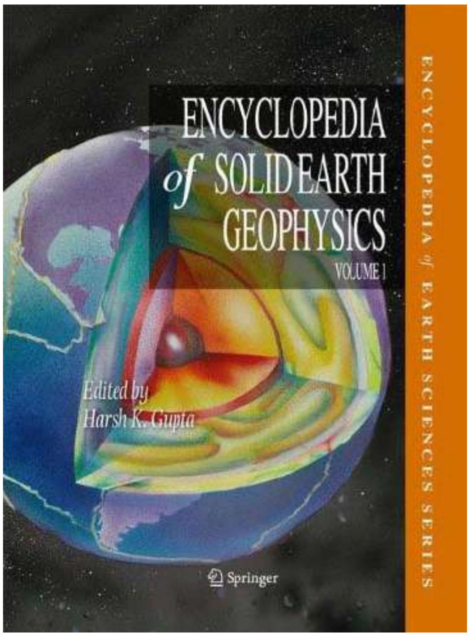


Figure 1. The expected ratio of peak vertical to peak horizontal ground acceleration predicted by equation (1) and (2).

Appendix D

"Introduction to Probabilistic Seismic Hazard Analysis"

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



Seismic Hazard

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

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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).

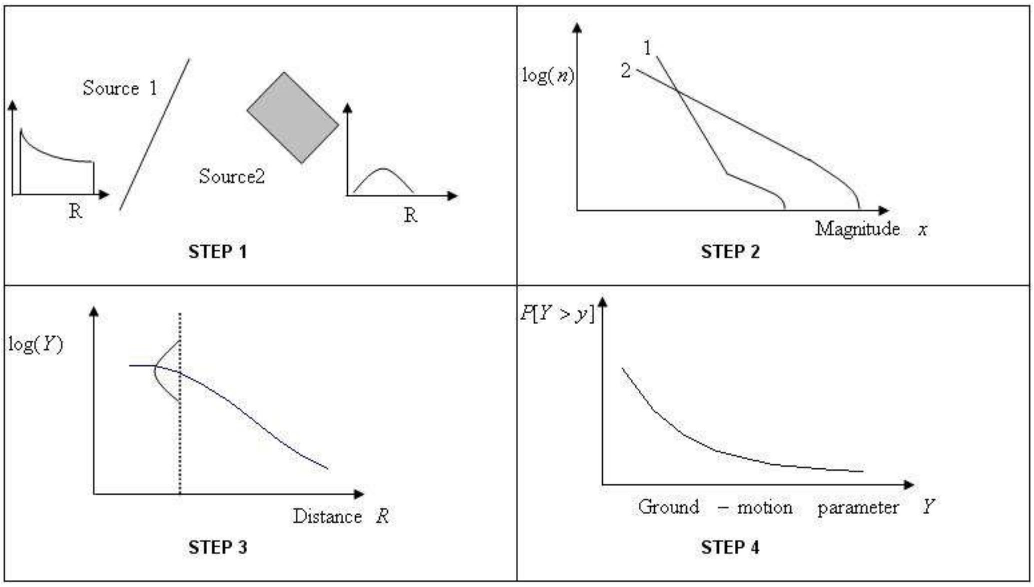

Figure 1. Four steps of a PSHA (modified from Reiter, 1990).

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)

$$\log(n) = a - bm, \quad (1)$$

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).

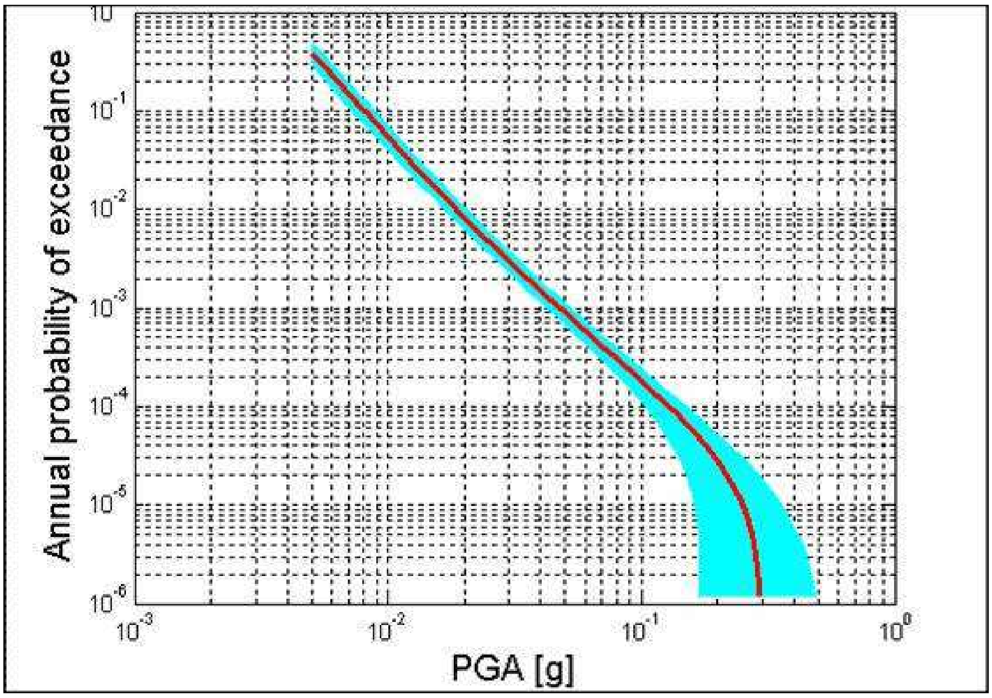

Figure 2. Example of a peak ground acceleration (PGA) seismic hazard curve and its confidence intervals

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 $(i = 1, 2, \dots)$ 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)

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

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

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

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,

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

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:

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

Whereβ = b ln10, 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)

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

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).

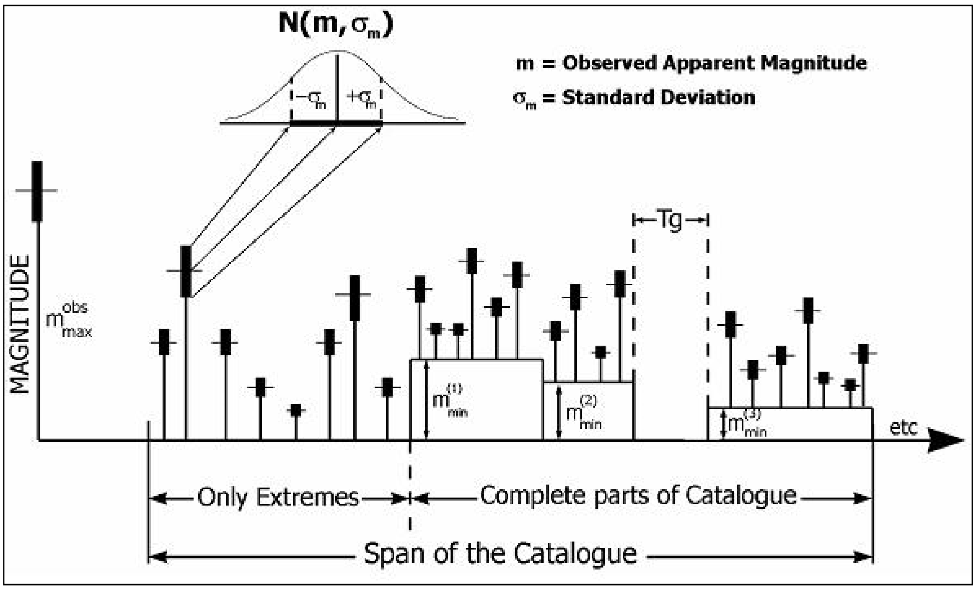

Figure 3. Illustration of data which can be used to obtain maximum likelihood estimators of recurrence oparameters by the procedure developed by Kijko and Sellevoll (1992). The approach permits the combination of largest earthquake data and complete data having variable periods of completeness. It allows 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 determine 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)

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

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

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

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)

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

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

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

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

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

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

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

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.

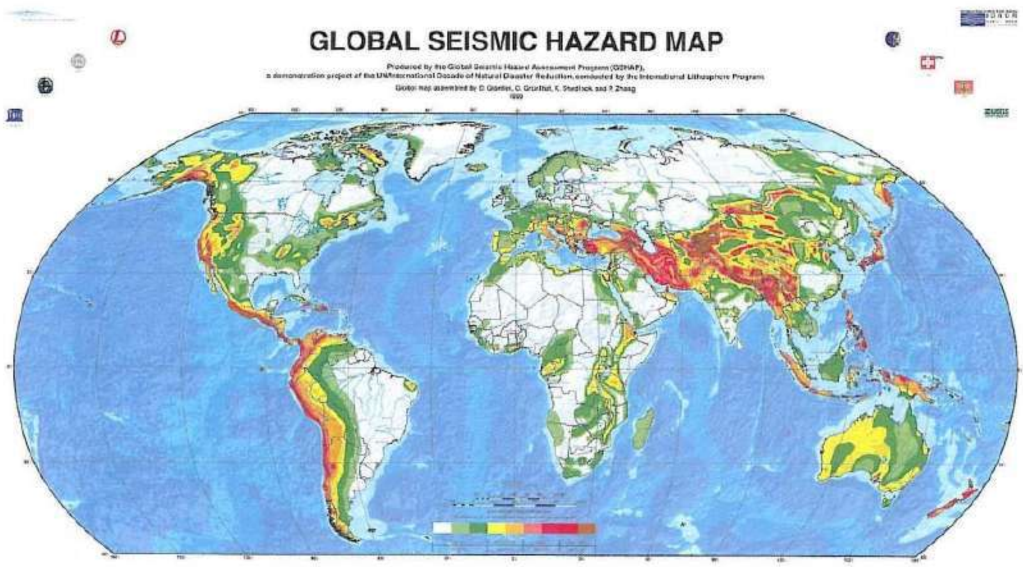

Figure 4. Example of product of PSHA. Map of seismic hazard of the world. Peak ground acceleration expected at 10% probability of exceedance at least once in 50 years. (From Giardini, 1999, http://www.gfz-potsdam.de/pb5/pb53/projects/gshap).

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).

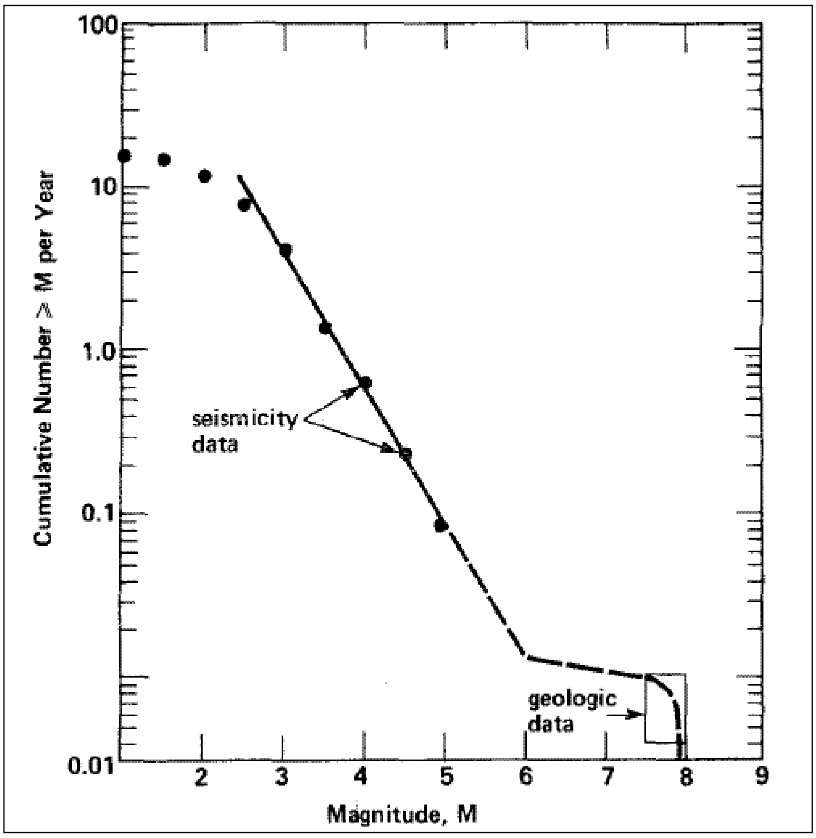

Figure 5. Gutenberg-Richter characteristic earthquake magnitude distribution. The model combines frequency-magnitude Gutenberg-Richter relation a with a uniform distribution of characteristic earthquakes. The model predicts higher rates of exceedance at magnitudes near the characteristic earthquake magnitude.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

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

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 $c_1, \ldots, c_6$ 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).

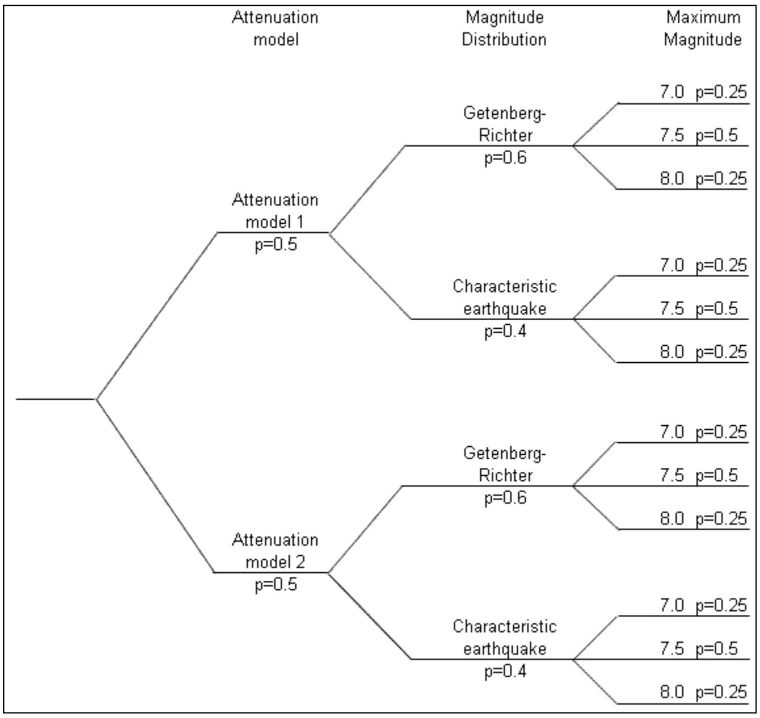

Figure. 6. An example of a simple logic tree. The alternative hypothesis accounts for uncertainty in ground motion attenuation relation, magnitude distribution model and the assigned maximum magnitude m_{max}.

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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