ESSENTIALS OF EARTHQUAKE HAZARD ASSESSMENT FOR DAMS

M.Ö. Erdik
Boğaziçi University, İstanbul, Turkey

TECHNICAL BASIS


- FERC Engineering Guidelines - USA Dams and HEPP’s

- Personal Experience
PRIMARY FACTORS TO CONSIDER IN SEISMIC HAZARD ASSESSMENT

A seismic hazard assessment is typically required to develop the seismic parameters that will be required for seismic design or performance assessment of dams. A seismic hazard assessment requires the following:

• Identification of potential sources of earthquakes.
• Evaluation of the characteristics of each potential earthquake source such as geological conditions, magnitudes and rates of activity.
• Empirical equations to compute ground motion amplitudes or intensities (i.e. attenuation equations).

Safety Evaluation Earthquake (SEE)

is that level of shaking for which damage can be accepted but for which there should be no uncontrolled release of water from the reservoir. (The SEE replaces the terms Maximum Design Earthquake (MDE) used in the first edition of this bulletin and Design Basis Earthquake (DBE) used in ICOLD Bulletin 46)

Operating Basis Earthquake (OBE)

is that level of shaking for which there should be no or insignificant damage to the dam and appurtenant structures.

Maximum Credible Earthquake (MCE)

is the largest reasonably conceivable earthquake magnitude that is considered possible along a recognized fault or within a geographically defined tectonic province.

MCE Ground Motion

The most severe ground motion affecting a dam site due to an MCE scenario is referred to as the MCE ground motion. Evaluation of the MCE ground motion is generally done using a deterministic approach. The return period of the MCE ground motion generally cannot be determined.
The Safety Evaluation Earthquake (SEE)
Maximum level of ground motion for which the dam should be designed or analyzed. Level of motion from the occurrence of a deterministically-evaluated maximum credible earthquake (MCE) or of the probabilistically-evaluated earthquake ground motion.

For high consequence dams the SEE ground motion parameters should be estimated at the 84th percentile level if developed by a deterministic approach, and need not have a mean annual exceedance probability smaller than 1/10,000 if developed by a probabilistic approach.

For moderate consequence dams the SEE ground motion parameters should be estimated at the 50th to 84th percentile level if developed by a deterministic approach, and need not have a mean AEP smaller than 1/3,000 if developed by a probabilistic approach.

For low consequence dams the SEE ground motion parameters should be estimated at the 50th percentile level if developed by a deterministic approach and need not have a mean AEP smaller than 1/1,000 if developed by a probabilistic approach.

It will be required at least that there is no uncontrolled release of water when the dam is subjected to the seismic load imposed by the SEE.

The Operating Basis Earthquake (OBE)
In theory the OBE can be determined from an economic risk analysis but this is not always practical or feasible. In many cases, it will be appropriate to choose a minimum return period of 145 years (i.e. a 50% probability of not being exceeded in 100 years).

OBE represents the level of ground motion at the dam site for which only minor damage is acceptable. The dam, appurtenant structures and equipment should remain functional and damage should be easily repairable, from the occurrence of earthquake shaking not exceeding the OBE.
Seismic Hazard Assessment
In general refers to the potentially damaging phenomena associated with earthquakes, such as ground shaking, liquefaction, landslides, and tsunami.
In more specific sense, seismic hazard (SHA) is the probability of experiencing a specified “intensity measure” of ground motion at a particular site, or over a region, in a given period.
SHA grew out of an engineering need for better designs in the context of structural reliability (Cornell, 1968, 1969).
SHA is also needed for the quantification of uncertainties involved in the hazard estimation process.

Probabilistic seismic hazard analysis (PSHA)
Deterministic seismic hazard analysis (DSHA)
Probabilistic Analysis

• Advantages
  – Manage Uncertainty
  – Treats Multiple sources
  – More mathematical rigor for ground motion
  – Superior for spectral ordinates
  – Can incorporate input from wide community of experts

• Disadvantages
  – Complex computation
  – Requires detailed investigation to define input to analysis
  – Can be Controversial

Constituent parts of the SHA
Seismic hazard assessment (DSHA and/or PSHA) encompasses, in general, the following ingredients:
• Earthquake source characterization in terms of their location and source physics.
• Determination of maximum magnitude earthquakes in each source.
• Ground motion attenuation relationships.
In addition to these, the PSHA needs:
• Earthquake occurrence statistics (frequency of occurrence of different magnitudes) in each source, and
• An appropriate probabilistic model
Components of PSHA

1. GEOLOGIC/SEISMOLOGIC RESEARCH
   - SEISMOLOGY
   - EARTHQUAKE CATALOG
   - SEISMIC SOURCE ZONES & FAULTS
   - GEOLOGIC, TECTONICS & GEOTECHNICAL

2. SEISMICITY ANALYSIS
   - RECURRENCE & Mmax
   - GROUND MOTION PREDICTION Eqns
   - LOGIC TREES
   - PSHA HAZARD AT ROCK

3. ENGINEERING ANALYSIS
   - CONTROLLING EVENTS
   - FIELD INVESTIGATION
   - SITE AMPLIFICATION
   - GMRS & Time Histories

SHA Methodology used for earthquake resistant design
PSHA can be summarized by the following total probability theorem:

\[
\lambda[X \geq x] \approx \sum_{i} \left( \int_{M_o}^{M_{\max}} \int_{R|M} \left( P[X \geq x|M,R] \times f_{M}(m) \times f_{R|M}(r|m) \right) dr \, dm \right)
\]

Where:
- \(\lambda[X \geq x]\) is the annual frequency that ground motion at a site exceeds the chosen level \(X = x\)
- \(\lambda\) is the annual rate of occurrence of earthquakes on seismic source \(i\), having magnitudes between \(M_o\) and \(M_{\max}\)
- \(M_{\max}\) is the maximum magnitude at the source
- \(P[X \geq x|M,R]\) denotes the conditional probability that the chosen ground motion level is exceeded for a given magnitude and distance
- \(f_{M}(m)\) is the probability density function of earthquake magnitude
- \(f_{R|M}(r|m)\) is the probability density function of distance from the earthquake source to the site of interest
- \(M_o\) is the minimum magnitude of engineering significance.

Mo is the minimum magnitude of engineering significance.
Deterministic Analysis

- **Advantages**
  - Adequate for "What if Scenarios"
  - Adequate where one feature controls the hazard
  - Useful to understand seismic attenuation

- **Disadvantages**
  - Poor management of uncertainty
  - Can not assess various "what if” scenarios
  - Difficult to compute reliable spectral ordinates

FIVE STEP PROCESS

- Step 1 – Geology, Tectonics & Geotechnical
- Step 2 – Seismology
- Step 3 – Ground Motion Prediction Equations
- Step 4 – Perform Seismic Hazard Analyses
- Step 5 – Define Seismic Design Response Spectra
Step 1 – Geology, Tectonics & Geotech

- Identify faults
  - Types, activity, $M_{\text{max}}$, Maps
- Identify Seismic Source Zones (SSZ’s)
  - Boundaries, recurrence relationships, $M_{\text{max}}$
- Define site stratigraphy
  - Types, thickness, depth, and dip
- Define ground water conditions
- Assign static and dynamic properties
  - Foundation & Embankment materials

Seismic Source Types

- **Criteria for Definition**
  - Tectonic processes and historical seismicity
  - Geology
  - Uniform Hazard
- **SSZ’s - Area Sources**
  - Areas defined by observed seismicity but no faults
  - Characterized by Gutenberg Richter Equation
- **Faults – Linear Sources**
  - a particular tectonic feature
- Background seismicity
Seismic Sources

The earthquake sources may be characterized as discrete faults in tectonically active regions (fault sources) or as areal zones with uniform seismicity (areal sources).

The geometric source zone parameters for areal and fault sources include the location, geometry, and for faults dip and width.

Fault sources can be line sources (two dimensional) or planar sources (three dimensional) modeling the distribution of seismicity over the fault plane.

Areal source zones are used to model spatial distribution of seismicity that cannot be specifically associated with major faults, background seismicity areas or in regions with unspecified faults. An areal seismic source zone is defined as a seismically homogenous area, in which every point within the source zone is assumed to have the same probability of being the epicenter of a future earthquake.

Background seismic zones are areal sources that can be defined to account for floating earthquakes not accounted by these sources and also to delineate zones where no significant earthquake has taken place for centuries.

Source Zoning for Italy

Structural kinematic model; colors refer to stress mechanisms, i.e. red compressive, green extensional

After CNR/IGNDT
A seismic source zonation for California.
(Frankel et al. 2002)
Segmentation
Segment length (or area) can constrain magnitude
Segments bounded by discontinuities
Geometric discontinuities - abrupt changes in strike, stepovers, gaps
Structural discontinuities - fault bifurcations, zones of increased structural complexity, intersections with other structures
Behavioral discontinuities - changes in slip rates, senses of displacement, creeping vs. locked behavior

Segmentation of San Andreas Fault, California

Working Group on California Earthquake Probabilities
Step 2 – Seismology

- Collect historical & instrumental records
- Estimate maximum and minimum depths of events
- Estimate the Causative Fault type & location
  - Strike Slip, Reverse, Normal, Combined
- Determine the recurrence rates (a & b parameters)
Earthquake Catalogs

- The Earthquake Catalogs for the Country
- Regional Catalogues
- International Seismological Centre

Earthquake Catalog

- Catalog analyses
  – Convert to moment magnitude scale (Mw)
  – De-clustered to remove dependent earthquakes
  – Assess completeness assessed as a function of magnitude
    • Based on observation of apparent rate as a function of time
    • Uncertainty in completeness is represented by use of two alternative completeness periods.
Earthquake Catalog Requirements

- Consistent in terms of magnitude units
- Declustered: Free of aftershocks and foreshocks
- Address catalog completeness

<table>
<thead>
<tr>
<th>Magnitude (Ms)</th>
<th>Completeness Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1985</td>
</tr>
<tr>
<td>4</td>
<td>1960</td>
</tr>
<tr>
<td>5</td>
<td>1930</td>
</tr>
<tr>
<td>6</td>
<td>1900</td>
</tr>
<tr>
<td>7</td>
<td>1800</td>
</tr>
</tbody>
</table>

Earthquake Catalog

- List of earthquakes
  - Time of occurrence
  - Magnitude
  - Location
- Used to define parameters of seismic sources
  - Recurrence rates
  - B-value
  - Probability of exceeding a given magnitude
Earthquake Activity Rates

The magnitude probability density function associated with the truncated exponential and characteristic earthquake models provides for the relative rate of occurrence of earthquakes at different magnitudes.

To obtain the absolute rate of occurrences, the activity rate ($n$) for each source zone needs to be determined. For this purpose approaches based on historical seismicity and/or geology (conservation of seismic moment) can be used.
Empirical Gutenberg-Richter Recurrence Relationship

\[ \log \lambda_m = a - bm \]

\[ \lambda_m = \text{mean rate of recurrence (events/year)} \]

\[ 1/\lambda_m = \text{return period} \]

\[ a \text{ and } b \text{ to be determined from data} \]

Truncated Exponential Model

The truncated exponential model is based on the well known Gutenberg-Richter magnitude recurrence relation. The Gutenberg-Richter relation is given by

\[ \log N(M) = a - bM \]

where \( N(M) \) is the cumulative number of earthquakes with magnitude greater than \( M \). The \( a \)-value is the log of the rate of earthquakes above magnitude 0 and the \( b \)-value is the slope on a semi-log plot (Figure 6-5). Since \( N(M) \) is the cumulative rate, then the derivative of \( N(M) \) is the rate per unit magnitude. This derivative is proportional to the magnitude pdf.

The probability density function for the truncated exponential model is given by the following equation. The model is truncated a \( M_{\text{min}} \) and \( M_{\text{max}} \) and \( \beta \) is \( \ln(10) \) times the \( b \)-value.

\[ f_{\text{TE}}(m) = \frac{\beta \exp(-\beta (m - M_{\text{min}}))}{1 - \exp(-\beta (M_{\text{max}} - M_{\text{min}}))} \]
Characteristic Earthquake Models

The exponential distribution of earthquake magnitudes works well for large regions; however, in most cases is does not work well for fault sources. For example of the San Andreas fault, while the small earthquakes approximate an exponential distribution, the rate of large earthquakes found using geologic studies of the recurrence of large magnitude earthquakes is much higher than the extrapolated exponential model. This discrepancy lead to the development of the characteristic earthquake model.

Individual faults tend to generate earthquakes of a preferred magnitude due to the geometry of the fault. The basic idea is that once a fault begins to rupture in a large earthquake, it will tend to rupture the entire fault segment. As a result, there is a “characteristic” size of earthquake that the fault tends to generate based on the dimension of the fault segment.

The fully characteristic model assumes that all of the seismic energy is released in characteristic earthquakes. This is also called the “maximum magnitude” model because it does not allow for moderate magnitude on the faults. The simplest form of this model uses a single magnitude for the characteristic earthquake (e.g. a delta function).
Probability density functions for magnitude, \( f(m) \); (a) truncated exponential and characteristic, (b) maximum magnitude.

### \( M_{\text{max}} \) Determination

- Maximum magnitude
  - Faults – Use Rupture length as basis
  - SSZ's – Add increment to maximum observed earthquake

- \( M_{\text{max}} \) usually defined with a three-point discrete probability distribution
MAXIMUM MAGNITUDES

Maximum magnitude represents a reasonable physical limit of the size of an earthquake that can be generated by an earthquake source that is related to the dimensions of the source or source segments.

The maximum magnitude in a source zone has been traditionally assessed as the maximum magnitude in the historical seismicity plus a half magnitude unit.

For specific faults the maximum magnitude has been traditionally associated with the earthquake that ruptures half of the total fault length. Recent investigations on maximum magnitude rely more on fault segmentation studies with single (i.e. characteristic earthquake) and cascaded segment ruptures.

In seismically inactive regions or in areal sources with no distinct faults the maximum earthquake sizes can be determined through analysis of historical seismicity.

\[ M_{\text{max}} \]

- Establish earthquake potential
- Empirical correlations
- Rupture length correlations
- Rupture area correlations
- Maximum surface displacement correlations
- "Theoretical" determination
- Slip rate correlations
- \( Mo = \mu A D \)
  - \( \mu = \text{shear modulus of rock} \)
  - \( A = \text{rupture area} \)
  - \( D = \text{average displacement over rupture area} \)
**Empirical Relationships between Moment Magnitude, $M_w$, Surface Rupture Length, $L$ (km), Rupture Area, $A$ (km$^2$), and Maximum Surface Displacement, $D$ (m)**

<table>
<thead>
<tr>
<th>Fault Movement</th>
<th>Number of Events</th>
<th>Relationship $M_w = a + b \log L$</th>
<th>$\sigma_{M_w}$ Relationship $\log L = 0.74M_w - 3.55$</th>
<th>$\sigma_{\log L, M_w}$ Relationship $\log D = 1.03M_w - 7.03$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strike slip</td>
<td>43</td>
<td>$M_w = 5.16 + 1.12 \log L$</td>
<td>0.28</td>
<td>0.23</td>
</tr>
<tr>
<td>Reverse</td>
<td>19</td>
<td>$M_w = 5.00 + 1.22 \log L$</td>
<td>0.28</td>
<td>0.20</td>
</tr>
<tr>
<td>Normal</td>
<td>15</td>
<td>$M_w = 4.86 + 1.32 \log L$</td>
<td>0.34</td>
<td>0.21</td>
</tr>
<tr>
<td>All</td>
<td>77</td>
<td>$M_w = 5.00 + 1.16 \log L$</td>
<td>0.28</td>
<td>0.22</td>
</tr>
<tr>
<td>Strike slip</td>
<td>83</td>
<td>$M_w = 3.98 + 1.02 \log A$</td>
<td>0.23</td>
<td>0.22</td>
</tr>
<tr>
<td>Reverse</td>
<td>43</td>
<td>$M_w = 4.33 + 0.90 \log A$</td>
<td>0.25</td>
<td>0.26</td>
</tr>
<tr>
<td>Normal</td>
<td>22</td>
<td>$M_w = 3.93 + 1.02 \log L$</td>
<td>0.25</td>
<td>0.22</td>
</tr>
<tr>
<td>All</td>
<td>148</td>
<td>$M_w = 4.07 + 0.98 \log L$</td>
<td>0.24</td>
<td>0.24</td>
</tr>
<tr>
<td>Strike slip</td>
<td>43</td>
<td>$M_w = 6.81 + 0.78 \log D$</td>
<td>0.29</td>
<td>0.34</td>
</tr>
<tr>
<td>Reverse</td>
<td>21</td>
<td>$M_w = 6.52 + 0.44 \log D$</td>
<td>0.52</td>
<td>0.42</td>
</tr>
<tr>
<td>Normal</td>
<td>16</td>
<td>$M_w = 6.61 + 0.71 \log D$</td>
<td>0.34</td>
<td>0.38</td>
</tr>
<tr>
<td>All</td>
<td>80</td>
<td>$M_w = 6.69 + 0.74 \log D$</td>
<td>0.40</td>
<td>0.42</td>
</tr>
</tbody>
</table>


*Regression relationships are not statistically significant at a 95% probability level (note inconsistency of regression coefficients and standard deviations).*

**Estimates based on Fault Length**

- Rupture length related to magnitude of event
- Maximum potential earthquake that can be produced by a fault can be related to fault length

*Long faults: can whole fault rupture at one time?*

**Wells and Coppersmith suggest:**

$$M_w = a + b \log L (\text{km}) \quad \text{[median]}$$

- **Strike slip:** $a = 5.16$, $b = 1.12$
- **Normal Thrust:** $a = 4.86$, $b = 1.32$
- **Reverse Fault:** $a = 5.00$, $b = 1.22$

**Example:**

- 43 km strike slip faulting
  $$M_w = 5.16 + 1.12 \log (43) = 7.0$$

**The standard deviations are:**

- $\sigma_{M_w} = 0.28$ for Strike Slip
- 0.34 for Normal Thrust Fault
- 0.28 for Reverse Fault

so for a 85% confidence level (+1$\sigma$) we would have:

$$M_{W,85} = M_w + \sigma_{M_w} = 7.28$$

Perhaps, this defines a maximum "credible" earthquake (MCE) for this fault
Step 4 – Select Ground Motion Prediction Equations

- Identify appropriate GMPE's - usually 3 to 5+

- Evaluate how the GMPEs fit the observed regional data to establish weights for logic tree
  - Stable Continental, Active, Subduction

- Address how epistemic uncertainties and aleatory variabilities will be addressed in the logic tree

ATTENUATION RELATIONSHIPS

Assessment of the seismic hazard requires an appropriate strong-motion attenuation relationship, which depicts the propagation and modification of strong ground motion as a function of earthquake size (magnitude) and the distance between the source and the site of interest.

It is important to note that the magnitude scale used in the recurrence relationships of the source zones and the unit of the source to site distance should be compatible with those utilized in the attenuation relationships chosen for the seismic hazard analysis.
The ground motion parameter PGA or SA is Log-Normally Distributed.
What do GMPE's look like?

\[ \ln S_a(T) = \mu(M, R, T, \theta) + \sigma_{\text{total}}(T) \varepsilon_{\text{total}}(T) \]

\[ \ln Y = b_1 + b_2(M - 6) + b_3(M - 6)^2 + b_4 \ln r + b_5 \ln \frac{V_s}{V_A} \]

\( b_1, b_2, b_3, b_5, b_v \) and \( V_A \) are regression parameters, \( r \) is a distance parameter, \( M \) is the magnitude.

\( V_s \) – average shear wave velocity of upper 30m of ground

Rock is generally >800m/s, stiff soil is 360-800m/s and soft soil is 180-360m/s
### List of pre-selected models for the main seismo-tectonic regimes in the GEM – PEER Global GMPEs project

#### Shallow crustal in tectonically active regions

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrahamson &amp; Silva (2008)</td>
<td>NGA model using worldwide data</td>
</tr>
<tr>
<td>Akkar &amp; Bommer (2010)</td>
<td>Model using Mediterranean and Middle Eastern data</td>
</tr>
<tr>
<td>Campbell &amp; Bozorgnia (2008)</td>
<td>NGA model using worldwide data</td>
</tr>
<tr>
<td>Chou &amp; Youngs (2008)</td>
<td>NGA model using worldwide data</td>
</tr>
<tr>
<td>Kanno et al. (2006)</td>
<td>Model using mainly Japanese data</td>
</tr>
<tr>
<td>McVerry et al. (2006)</td>
<td>Model using mainly New Zealand data</td>
</tr>
<tr>
<td>Zhao et al. (2006)</td>
<td>Model using mainly Japanese data</td>
</tr>
</tbody>
</table>

#### Subduction

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC Hydro Model, Abrahamson et al. (2012)</td>
<td>Worldwide</td>
</tr>
<tr>
<td>Arroyo et al. (2010): Interface model for Mexico (complementary to Garcia et al., 2005)</td>
<td></td>
</tr>
<tr>
<td>Garcia et al. (2005): Intraslab model for Mexico (complementary to Arroyo et al., 2010)</td>
<td></td>
</tr>
<tr>
<td>Kanno et al. (2006): Japan</td>
<td></td>
</tr>
<tr>
<td>Lin &amp; Lee (2008): Taiwan</td>
<td></td>
</tr>
<tr>
<td>McVerry et al. (2006): New Zealand</td>
<td></td>
</tr>
<tr>
<td>Youngs et al. (1997): Worldwide</td>
<td></td>
</tr>
<tr>
<td>Zhao et al. (2006) with modifications by Zhao (2010): Japan</td>
<td></td>
</tr>
</tbody>
</table>
List of pre-selected models for the main seismo-tectonic regimes in the GEM – PEER Global GMPEs project

- Campbell (2003): Hybrid model for eastern North America
- Douglas et al. (2006): Hybrid model for southern Norway
- Frankel et al. (1996) as parameterized by EPRI (2004): Stochastic model for eastern North America
- Pezeshk et al. (2011): Hybrid model for eastern North America
- Raghu Kanth & Iyengar (2006, 2007): Peninsular India
- Silva et al. (2002): Stochastic model for eastern North America
- Somerville et al. (2009): Simulation-based models for Australia

---

**Figure 4.3.** Plot of PGA versus $R_{RUP}$ for the Parkfield dataset, along with the predicted ground motion using the average site characteristic among the 85 stations, $V_{S30} = 403.2$ m/s. Graphically, the models have similar patterns of attenuation with distance. The increase in ground motion variability at distances less than 10 km is clearly observed. Points are separated into the categories of soil sites ($180 \leq V_{S30} < 450$ m/s) and rock sites ($450 \leq V_{S30} < 1300$ m/s).
AS: Abrahamson and Silva (2008);
BA: Boore and Atkinson (2008);
CB: Campbell and Bozorgnia (2008);
CY: Chiou and Youngs (2008);
ADSS: Ambraseys et al. (2005);

GEOMETRIC MEAN and MAXIMUM SPECTRA
1999 Kocaeli Earthquake – Düzce Record
(Mw = 7.5, Strike-Slip, Df = 15.4 km, Vs30 < 276 m/s)

Kircher et al., 2011
Geometric Mean
(1-Second Response of the Kocaeli-Duzce Record)

Kircher et al., 2011

MAXIMUM AMPLITUDE
(1-Second Response of the Kocaeli-Duzce Record)

Kircher et al., 2011
Step 5 – Perform PSHA and DHSA

- Basic Tenets
  - Use same data for both PSHA and DSHA except that no recurrence data is used for DHSA
  - The PSHA results should prevail, but DSHA should serve as a basic check on PSHA
PROBABILITY MODELS

For earthquake engineering and earthquake insurance purposes the annual rate (frequency) of exceeding a specific ground motion parameter level $x$ at a given site needs to be converted to probabilities that $x$ is exceeded at least once during a specific time period. For this conversion the simplest, and somewhat standard, approach is to model the temporal occurrence of earthquakes by the “Simple Poisson Model”.

Poisson model does not have a memory, or, in other words, the rate of occurrence is independent of the time of the past earthquake and is determined only by the average frequency (rate) of past earthquakes. For these faults, with sufficient information on paleo-seismicity and strain rates, the earthquake occurrence models that account for the past activity of large magnitude (characteristic) earthquakes should be considered

**Time Dependent Models**

Renewal Model is used to model the temporal occurrence of large magnitude earthquakes. The conditional probability, $P(T, \Delta T)$, that a large magnitude earthquake occurs in the next $\Delta T$ years given it has not occurred during the previous $T$ years is given by the following expression:

$$ P(T, \Delta T) = \frac{\int_T^{T+\Delta T} f(t) \, dt}{\int_T^{T+\Delta T} f(t) \, dt} $$

Where $f(t)$ is the probability density function of the recurrence interval of the large magnitude earthquake, generally described by log-normal, Weibull, gamma and Brownian Passage Time (BPT) distributions.
Step 5 – Perform PSHA and DHSA

- **PSHA**
  - Develop Logic trees
    - Use branches for Epistemic Uncertainty
    - Expect 3,000 to 100,000 branches
  - Decide on Design Return Period
    - 10,000 years – very high hazard or very large investment
    - 2500 years – high hazard or large investment
    - 1000 years – low hazard
  - Develop Hazard Curves
    - Use V&V’d Computer Code with linear & area SSZ’s
    - Develop mean, median, + & -1 $\sigma$ and 2 $\sigma$
Managing uncertainty in GMPE’s

- **Aleatory**

  - Due to the unpredictable nature of future earthquakes
  - Measured by distributions (pdfs)
  - Included in hazard calculations via integrals

- **Epistemic**

  - The result of our incomplete knowledge of earthquake processes
  - Estimated by “expert judgements”
  - Included in hazard calculations via Logic Tree

Managing uncertainty in GMPE’s

- **Aleatory**

  - P[Acc>a | m]

- **Epistemic**

  - Abrahamson and Silva 2008 (NGA) (0.20)
  - Chiou and Youngs 2008 (NGA) (0.20)
  - Campbell and Bozorgnia 2008 (NGA) (0.20)
  - Boore and Atkinson 2008 (NGA) (0.20)
  - Ambraseys et al. 2005 (0.20)
Logic Tree Approach

Each possible combination of inputs produces a different output, so that a typical application of the process would produce thousands of possible results.

In seismic hazard assessment different alternatives of attenuation relationships, source geometry, maximum magnitude and recurrence relationship parameters can be used.

Each alternative is represented by a discrete distribution of values, with subjective probabilities used to describe the credibility of each alternative.

The weights assigned are proportional to our estimate of the likelihood of each model (i.e. branch) and the sum of the weights is unity.

The number of viable alternative models limit the number of these branches and hence the treatment of the epistemic uncertainty.

Branches on the logic tree should reflect alternative estimates of the parameters and models included in the hazard integral.

Weights of each level sum up to 1
Example

The sense of slip on a fault that is used for computing the magnitude is uncertain.

Assume two possible alternatives: strike slip and reverse. The assigned weight reflects a higher probability of reverse faulting.

---

Logic tree representing fault data (Pacific Gas and Electric, 1988). Values in parentheses are probabilities; h = horizontal component of slip rate; v = vertical component of slip rate.
Step 5 – Perform PSHA and DHSA

- PSHA Cont'
  - Develop UHRS at top of hard rock for selected Return Period

  - Perform De-aggregation Analysis

  - Determine governing Scenario Earthquakes for DSHA
Hazard Curves
PSHA yields the annual probability of exceedance of different amplitudes for each ground motion parameter (descriptor) of interest. A plot of these amplitudes against the probability of exceedance is called the “ground motion hazard curve”. Hazard curves provide plots of the annual probability of exceedance (or the average return period) of a selected hazard parameter (i.e. PGA or Spectral Acceleration) as a function of the amplitude of that parameter at a given location.
PHA hazard curves. Mean, median, 16th and 84th-percentile values indicated.

**Typical Results - Hazard curves**

[Graph showing hazard curves with various probability levels indicated.]
**Uniform Hazard Spectra (UHS)**

In the past, the design response spectrum used for earthquake resistant design was pegged to the PGA obtained on the basis of a PSHA. During the last decade, it has become standard earthquake engineering practice to construct the design spectrum (UHS) based on the probabilistic acceleration spectrum amplitudes, providing a better representation of site-specific characteristics. 

Since the same probabilities of exceedance are associated with each spectral acceleration values used in this construction, the response spectrum defined by this procedure is called the equal or uniform hazard or equi-risk spectrum.

Such a spectrum cannot be related to a physically realizable single earthquake since the low period regions of the spectrum would be controlled by medium magnitude near field earthquakes, whereas the high period regions would be controlled by somewhat distant large magnitude events.

---

**Uniform Hazard Spectrum**

Developed from *probabilistic* analysis.
- Represents contributions from small local and large distant earthquakes.
- May be overly conservative for modal response spectrum analysis.
De-aggregation Results (typical)

- At 10,000 yr Return Period
  - For 10-Hz, nearby earthquakes with Mw of 5 to 6 dominate the hazard
  - For 1-Hz SA, nearby earthquakes with Mw 5.5 to 6.5 and distant earthquakes with Mw 7 to 8 are both significant contributors to hazard
Deaggregation for T=1 sec for a return period of 475 years (the hazard is dominated by distant earthquakes with large magnitudes).
HAZARD DEAGGREGATION FOR LONG PERIODS

Although there is some slight variation with respect to distance, it can be assessed that with engineering accuracy, the 475 year average return period SD(10s) can be obtained as median-plus-1.3 standard deviation and the 2475 year average return period SD(10s) can be obtained as median-plus-2.0 standard deviation.
Step 5 – Perform PSHA and DHSA

- DSHA
  - Select Scenario Earthquakes for each SSZ and Fault – Consider De-aggregation Results
  
  - Postulate occurrence of Scenario Earthquake at closest point to Site
  
  - Select GMPE’s for each SSZ & Fault

Step 5 – Perform PSHA & DSHA (cont.)

- Compute DSHA Response Spectra and PGA for each Scenario Earthquake \((\text{mean} \& \text{mean} + 1 \sigma)\)

- Compare/Combine with PSHA

- Select governing Response Spectra
Relationship Between Maximum Amplitude and Geometric Mean (GMRotI50)

What Controls the Level of Shaking?

- **Magnitude**
  - Larger faults, stronger shaking, longer duration, and energy released over a larger area,

- **Distance from fault**
  - Shaking decays with distance

- **Site Effects**
  - Very soft soils amplify the shaking

- **Focusing**
  - Local pockets of higher shaking (lens effects)

- **Directivity (location of epicenter)**
  - Strongest shaking in direction of rupture

DESIGN BASIS GROUND MOTION
Site Amplification
(Seed et al.)
Directivity Effects on Ground Motion Amplitudes

- Increase in the amplitude of long period ground motion for rupture toward the site
- Decrease in the amplitude of long period ground motion for rupture away from the site
- Fault normal component is larger than the fault parallel component at long periods
1992 Landers Earthquake

Fault Normal
- Forward directivity region
- San Andreas 135 km west
- Rupture propagation
- Epicenter

Fault Parallel
- Backward directivity region
- Joshua Tree 42 km south
- 225.77 cm
- 183.79 cm

Directivity Pulse

Fling

Graphs showing
- Acceleration vs. Period
- Displacement vs. Period
Modification factor for the directivity-related spatial variation of average horizontal response spectral acceleration (from Somerville et al, 1997)

An approximate relationship between the peak velocity PGV on soil of the near-fault fault-normal forward directivity pulse and the moment magnitude $M_w$ and closest distance $R$ is:

$$\log_{10} \text{PGV} = -1.0 + 0.5 M_w - 0.5 \log_{10} R$$

**NARROWBAND DIRECTIVITY MODEL**

(Pulse Spectrum Based)
Seismic Design Basis

- Seismic Design Response Spectra
- Determine Governing Magnitude
- Develop Matching Time History

ACCELERATION TIME HISTORY MODELS
(ICOLD, 2014):

1. The three components of the spectrum-matched (synthetic) acceleration time histories must be statistically independent.
2. The acceleration time histories of the horizontal earthquake components may be assumed to act in along-river and across-river directions. No modifications in the horizontal earthquake components are needed if they are applied to other directions, i.e. directivity and near-fault effects do not have to be taken into account.
3. In the case of dams, which are susceptible to damage processes which are governed by the duration of strong ground shaking such as, e.g., the build-up of pore pressures in fill dams or the sliding movement of Slopes or concrete blocks, earthquake records with long duration of strong ground shaking shall be used.
4. For the safety check of a dam at least three different earthquakes shall be considered for the SEE ground motion.