Lecture 12: Introduction to seismic hazard analysis; methods; Deterministic and probabilistic; suitable method for your project; attenuation models and simulation of strong ground motion

Topics

- Introduction to Seismic Hazard Analysis
- Representations of Seismic Hazard
- Data completeness
- Recurrence Relation
- Gutenberg-Richter recurrence law
- Mmax Estimation
- Predictive relationships
- Deterministic Seismic Hazard Analysis
- Probabilistic Seismic Hazard Analysis
- Applicability of DSHA and PSHA
- Summary of uncertainties
- Uncertainty in the Hypocentral Distance
- Regional Recurrence
- Deaggregation
- Uniform hazard spectrum (UHS)
- Logic tree methods
- Ready Made Software for PSHA
- Attenuation models
- Simulation of Strong Ground Motion
- Forward modeling in strong ground motion seismology

Keywords: *Seismic Hazard Analysis, Deterministic, Probabilistic, Attenuation Models*

Topic 1

Introduction to Seismic Hazard Analysis

- Seismic hazard is defined as any physical phenomenon, such as ground shaking or ground failure, which is associated with an earthquake and that, may produce adverse effects on human activities.

- Seismic hazard analyses involve the quantitative estimation of ground-shaking hazards at a particular site. Seismic hazards may be analyzed deterministically, as when a particular earthquake scenario is assumed, or probabilistically, in which uncertainties in earthquake size, location, and time of occurrence are explicitly considered.

- To evaluate the seismic hazards for a particular site or region, all possible sources of seismic activity must be identified and their potential for generating future strong ground motion evaluated. Identification of seismic sources requires some detective work; nature's clues, some of which are obvious and others quite obscure, must be observed and interpreted.

- Seismic hazard analysis involves the quantitative estimation of ground shaking hazards at a particular area. The most important factors affecting seismic hazard at a location are:
  1. Earthquake magnitude
  2. the source-to-site distance
  3. earthquake rate of occurrence (return period)
  4. duration of ground shaking

- **Earthquake Magnitude** - Magnitude is the most common measure of an earthquake's size. It is a measure of the size of the earthquake source and is the same number no matter where you are or what the shaking feels like. Magnitudes can be based on any of the following:

  1. Ml **-** local magnitude is defined as the logarithm of the maximum trace amplitude recorded on a Wood-Anderson seismometer located 100km from the epicenter of the earthquake for magnitudes of 6.8 or greater, and hence is not useful for very strong earthquakes.

  2. Mb – Body wave magnitude is based on the longitudinal wave amplitude and their period. This magnitude scale becomes insensitive to the actual size of an earthquake for magnitudes of 6.4 or greater, and hence is not useful for very strong earthquakes.

  3. Ms **-** surface wave magnitude is based on the amplitude of maximum ground displacement caused by Rayleigh waves with a period of about 20 seconds and the epicentral distance of the seismometer measured in degrees. This magnitude scale becomes insensitive to the actual size of an earthquake for magnitudes of 8.4 or greater and hence, is not useful for very strong earthquakes. The total seismic energy released during an earthquake and the Magnitude Ms is given as

$$\log_{10} E_0 = 4.8 + 1.5Ms \qquad (12.1)$$

  4. Mw – Moment magnitude is bases on the seismic moment M_0. This magnitude does not have an upper limit. Where Lf and Wf are the length and width of a fault area, Sf is the average slip on the fault during an earthquake in meters, μ is shear modulus of the Earth's crust.

$$Mw = \frac{2}{3}\log_{10}(M_0) - 6.1 \qquad (12.2)$$

$$Mo = Lf.Wf.Sf.\mu \quad (12.3)$$

- Present practice appears to be moving towards the use of moment magnitude in preference to other magnitudes. Many earthquake magnitudes are defined using different magnitude scales and, therefore, a conversion between magnitudes is applied. The conversion relationships are usually specified when different magnitude scales are used. Ambraseys derived the following relationships between various common earthquake magnitude scales:

$$0.77m_b - 0.64M_L = 0.73 \quad (12.4)$$

$$0.86m_b - 0.49M_s = 1.94 \quad (12.5)$$

$$0.80M_L - 0.60M_s = 1.04 \quad (12.6)$$

- Chen and Chen provided the following relationships between $\log_{10}(M_0)$ and Ms.

$$\log 10(M_0) = Ms + 12.2 \quad \text{for } Ms \le 6.4 \quad (12.7)$$

$$\log 10(M_0) = 1.5Ms + 9.0 \quad \text{for } 6.4 < Ms \le 7.8 \quad (12.8)$$

$$\log 10(M_0) = 3.0Ms - 2.7 \quad \text{for } 7.8 < Ms \le 8.5 \quad (12.9)$$

The source-to-site distance - Much of the energy released by rupture along a fault takes the form of stress waves. As stress waves travel away from the source of an earthquake, they spread out and are partially absorbed by the materials they travel through. As a result, the specific energy decreases with increasing distance from the source. The distance between the source of an earthquake and particular site can be interpreted in different ways. Different distance used in engineering seismology is given in Figure 12.1.

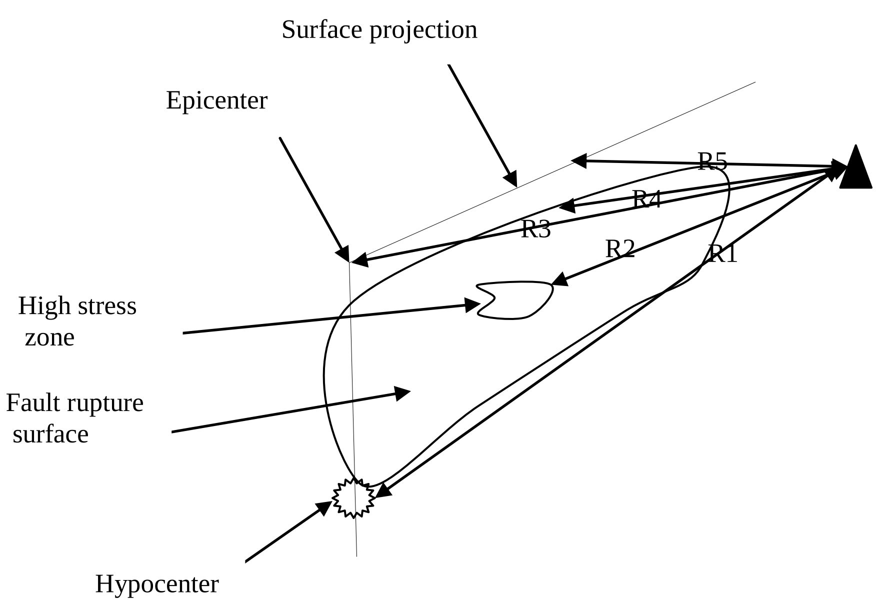


Fig 12.1: Various measures of distance used in strong –motion predictive relationships

- R1 and R2 are the hypocentral and epicentral distances, which are the easiest distances to determine after an earthquake. If the length of fault rupture is a significant fraction of the distances between the fault and the site, however, energy may be released closer to the site, and R1 and R2 may not accurately represent the “effective distance”.

- R3 is the distance to the zone of highest energy release. Since rupture of this zone is likely to produce the peak ground motion amplitudes, it represents the best distance measure for peak amplitude predictive relationships. Unfortunately, its location is difficult to determine after an earthquake and nearly impossible to predict before an earthquake.

- R4 is the closest distance to the zone of rupture and R5 is the closest distance to the surface projection of the fault rupture.

- **Earthquake rate of occurrence (return period)** - A return period is an estimate of the interval of time between earthquake. It is a statistical measurement denoting the average recurrence interval over an extended period of time, and is usually required for risk analysis.

- The theoretical return period is the inverse of the probability that the event will be exceeded in any one year. While it is true that a 10-year event will occur, on average, once every 10 years and that a 100-year event is so large that we expect it only to occur every 100 years, this is only a statistical statement: the expected number of 100-year events in an n year period is n/100, in the sense of expected value.
- Similarly, the expected time until another 100-year event is 100 years, and if in a given year or years the event does not occur, the expected time until it occurs remains 100 years, with this "100 years" resetting each time.

- It does not mean that 100-year earthquakes will happen regularly, every 100 years, despite the connotations of the name "return period"; in any given 100-year period, a 100-year earthquakes may occur once, twice, more, or not at all.

- Note also that the estimated return period is a statistic: it is computed from a set of data (the observations), as distinct from the theoretical value in an idealized distribution. One does not actually know that a certain magnitude or greater happens with 1% probability, only that it has been observed exactly once in 100 years.

- This distinction is significant because there are few observations of rare events: for instance if observations go back 400 years, the most extreme event (a 400-year event by the statistical definition) may later be classed, on longer observation, as a 200-year event (if a comparable event immediately occurs) or a 500-year event (if no comparable event occurs for 100 years).

- Further, one cannot determine the size of a 1,000-year event based on such records alone, but instead must use a statistical model to predict the magnitude of such an (unobserved) event.

Topic 2

Representations of Seismic Hazard

- The seismic hazard can be expressed in different ways: from simple observed macroseismic fields, to seismostatistical calculations for analyzing earthquake occurrences in time and space and assessing their dynamic effects in a certain site or region, to sophisticated seismogeological approaches for evaluating the maximum expected earthquake effects on the Earth's surface.

- Representation of seismic hazard and ground motion includes
  (1) The selection and utilization of national ground motion maps;
  (2) The representation of site response effects; and
  (3) The possible incorporation of other parameters and effects, including energy or duration of ground motions, vertical ground motions, near source horizontal ground motions, and spatial variations of ground motions.

- Seismic hazard can be represented in different ways but most frequently in terms of values or probability distributions of accelerations, velocities, or Displacements of either bedrock or the ground surface:

  1. The peak ground acceleration, ground acceleration time history or response spectral acceleration are useful because the product of a mass and the acting acceleration equals the magnitude of inertial force acting on the mass. However, peak acceleration occurs in high frequency pulses at infrequent intervals during the time history of ground vibration, and thus contains only a small fraction of the emitted seismic energy. For this reason peak acceleration is not suitable as a single measure of ground motion representation (e.g. Sarma and Srbulov, 1998).
  2. The peak ground velocity, ground velocity time history or response spectral velocity are useful because the product of square of velocity and a half of mass equals the amount of kinetic energy of the mass. Ground motions of smaller amplitude but longer duration frequently results in larger ground velocity and more severe destruction capability of ground shaking (e.g. Ambraseys and Srbulov,1994).
  3. The peak ground displacement, ground displacement time history or response spectral displacement of a structure are useful since damage of structures subjected to earthquakes is certainly expressed in deformations (e.g. Bommer and Elnashai, 1999).

- Ground acceleration, velocity and displacement are related among them because integration or differentiation in time of one of them produces another.

- Time histories of ground motions are often used in practice for non-linear analyses when damage caused by ground shaking can accumulate in time. Single peak values are poor indicators of earthquake destructiveness, so time histories of ground motion are usually considered for important, large, expensive and unusual structures and ground conditions. Response spectral values are a compromise between the singular values and a complete ground motion definition in time.

Topic 3

Data completeness

- Important step in any earthquake data analysis is to investigate the available data set to asses its nature and degree of completeness. Incompleteness of available earthquake data make it difficult to obtain fits of Gutenberg-Richter recurrence law that is thought to represent true long term recurrence rate.

- Uncertainty in size of earthquakes produced by each source zone can be described by various recurrence laws. The Gutenberg-Richter recurrence law that assumes an exponential distribution of magnitude is commonly used with modification to account for minimum and maximum magnitudes and is given by:

$$\text{Log}N = a - bM \tag{12.10}$$

- For a certain range and time interval, the above equation will provide the number of earthquakes, (N) with magnitude, (M) where 'a' and 'b' are positive, real constants. 'a' describes the seismic activity (log number of events with M=0) and 'b' which is typically close to 1 is a tectonics parameter describing the relative abundance of large to smaller shocks.

- The problem of data incompleteness can be overcome by the method proposed by Stepp (1972). In this method analysis is carried out by grouping the earthquake data into several magnitude classes and each magnitude class is modeled as a point process in time.

- By taking the advantage of the property of statistical estimation that variance of the estimate of a sample mean is inversely proportional to the number of observations in the sample (Stepp, 1972). Thus the variance can be made as small as desired by making the number of observation in the sample large enough, provided that reporting is complete in time and the process is stationary i.e. the mean variance and other moments of each observations remains the same.

- In order to obtain an efficient estimate of the variance of the sample mean, it is assumed that the earthquake sequence can be modeled by the Poisson distribution. If k_1, k_2, k_3…..k_n are the number of earthquakes per unit time interval, then an unbiased estimate of the mean rate per unit time interval of this sample is:

$$\lambda = \frac{1}{n}\sum_{i=1}^{n} k_i \qquad (12.11)$$

- And its variance is:

$$\sigma_{\lambda}^{2} = \frac{\lambda}{n} \qquad (12.12)$$

- Where n is the number of unit time intervals. Taking the unit time interval to be one year gives a standard deviation of:

$$\sigma_{\lambda} = \frac{\sqrt{\lambda}}{\sqrt{T}} \qquad (12.13)$$

- Where T is the sample length. Hence by assuming stationary process, one can expect that σ_{λ} behaves as $\frac{1}{\sqrt{T}}$ in the subintervals, in which the mean rate of occurrence in a magnitude class is constant. In other words when λ is constant, and then the standard deviation σ_{λ} varies as $\frac{1}{\sqrt{T}}$ where T is the time interval of the sample. If the mean rate of occurrence is constant we expect stability to occur only in the subinterval that is long enough to give a good estimate of the mean but short enough that it does not include intervals in which reports are complete (Stepp, 1972).

- The rate of earthquake occurrence as a function of time interval is given as N/T where N is the cumulative number of earthquakes in the time interval T, for subintervals of the 200-year sample. These data are used to determine the standard deviation of the estimate of the mean through the equation 2.13.

- Below figure reveals several features significant to statistical treatment of earthquake data regardless of whether one uses empirical relationship log N = a – b M with the extreme value distribution or other statistical approaches.

- For each magnitude interval in the Figure 12.2 the plotted points are supposed to define a straight line relation as long as the data set for the magnitude interval is complete. For a given seismic region the slope of the lines for all magnitude intervals should be same.

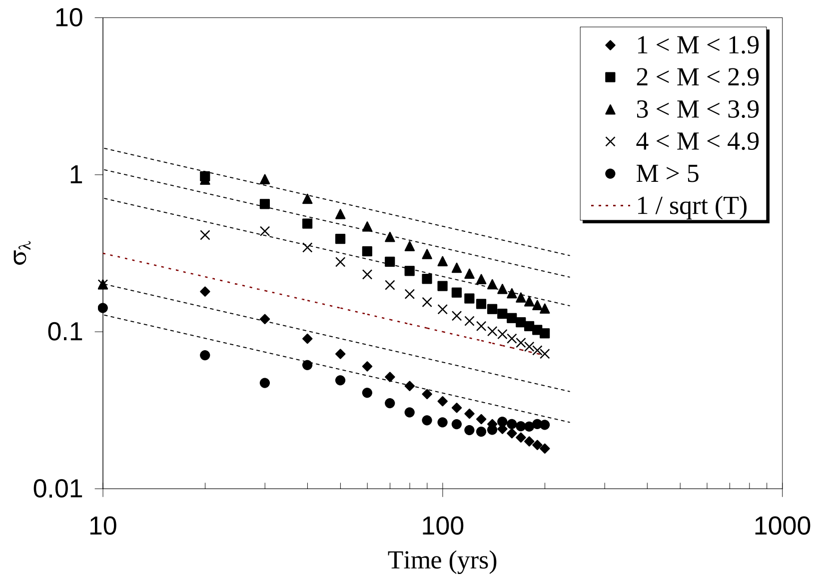


Figure 12.2: Variance of seismicity rate for different magnitude intervals and different lengths of moving time windows

Topic 4

Recurrence Relation

- The distribution of earthquake sizes in a given period of time is described by a recurrence law. Frequency of earthquakes recurrence is important because frequent earthquakes are likely to cause more cumulative damage than the same size rare earthquakes, which usually occur within interiors of tectonic plates (i.e. within the continents). Different rates of occurrence are proposed but most frequently referred are:
  1. Poisson process in which earthquakes occurs randomly, with no regard to the time, size or location of any preceding event. This model does not account for time clustering of earthquakes and may be appropriate only for large areas containing many tectonic faults. The probability of at least one exceedance of a particular earthquake magnitude in a period of t years P[N≥1] is given by the expression:

$$P[N \geq 1] = 1 - e^{-\lambda.t} \tag{12.14}$$

     Where λ is the average rate of occurrence of the event with considered earthquake magnitude. Cornell and Winterstein (1986) have shown that the Poisson model should not be used when the seismic hazard is dominated by a single source for which the return period is greater than the average return period and when the source displays strong characteristic-time behavior.

2. Time predictable, which specifies a distribution of the time to the next earthquake that depends on the magnitude of the most recent earthquake.
3. Slip predictable, which considers the distribution of earthquake magnitude to depend on the time since the most recent earthquake.

Topic 5

Gutenberg-Richter recurrence law

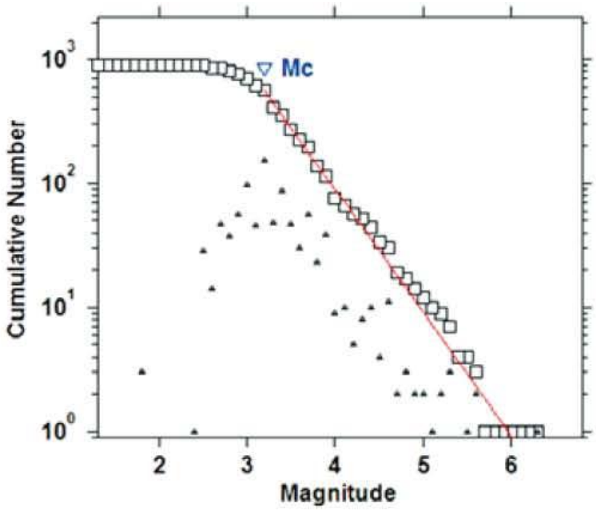
- Recurrence relations are a crucial component of seismic hazard analysis. They are the means of defining the relative distribution of large and small earthquakes and incorporating the seismic history into the hazard analysis. On the basis of worldwide seismicity data, Gutenberg and Richter established the loglinear relation (G-R line)

$$\log 10n(M) = a - bM \tag{12.15}$$

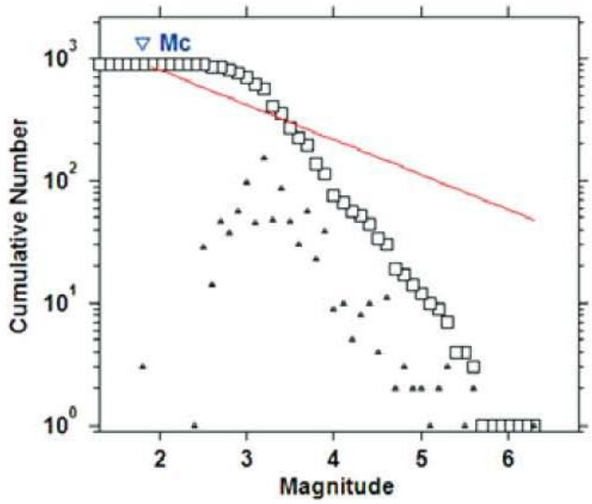
- Here N(M) is the number of earthquakes per year with a magnitude equal to or greater than M and a and b are constants for the seismic zone. N is associated with a given area and time period. The constant ‘a’ is the logarithm of the number of earthquakes with magnitudes equal to or greater than zero. The constant ‘b’ is the slope of the distribution and controls the relative proportion of large to small earthquakes

- A critical issue to be addressed before carrying out seismic hazard analysis is to assess the quality, consistency and homogeneity of the earthquake catalogue. The catalogues prepared should thus undergo a quality check especially for cutoff magnitude which has direct bearing on the estimation of a and b values of the Gutenberg–Richter relationship.

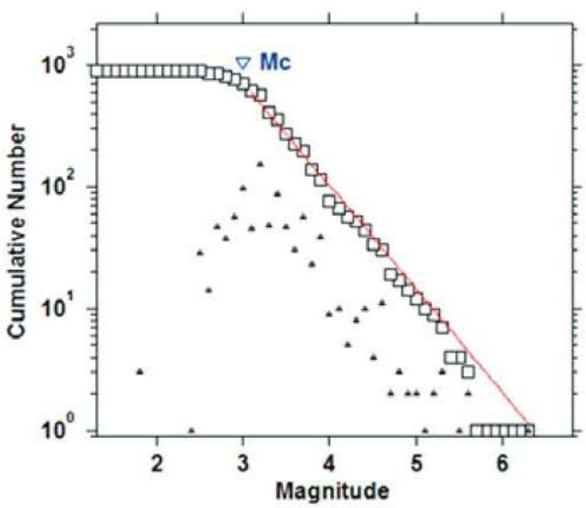
- There are nine methods using which the a, b and Mc values are estimated. The nine methods include the estimation of a, b and Mc are
    1. Maximum Curvature method (M1),
    2. Fixed Mc = Mmin (M2),
    3. Goodness of fit Mc90 (M3) and
    4. Mc95 (M4),
    5. best combinations of Mc90 and Mc95 and maximum curvature (M5),
    6. entire magnitude range (M6),
    7. Shi and Bolt (1982) method (M7),
    8. Bootstrap method (M8) and
    9. Cao and Gao (2002) method (M9).



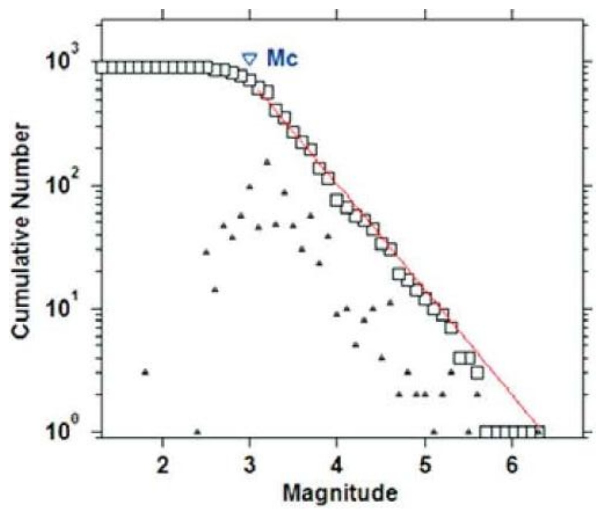
(a)Maximum Curvature method



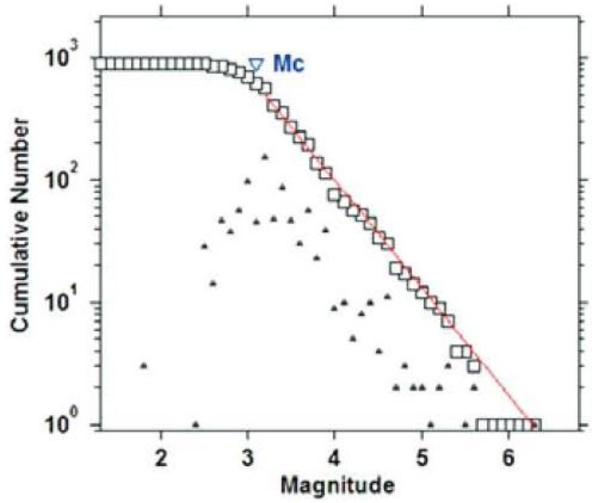
(b) Fixed Mc = Mmin



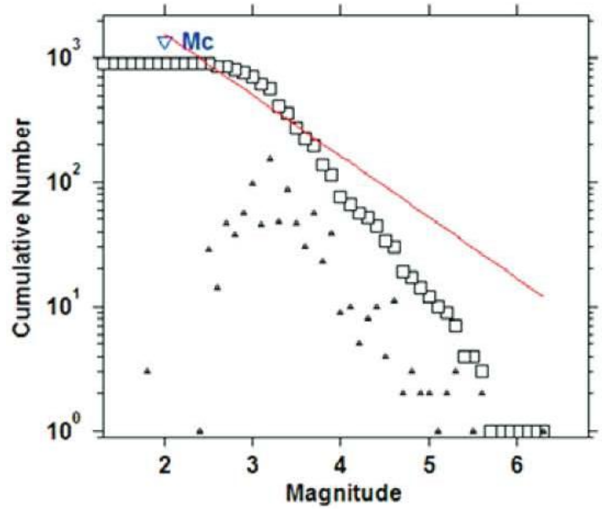
(c) Goodness of fit mc90



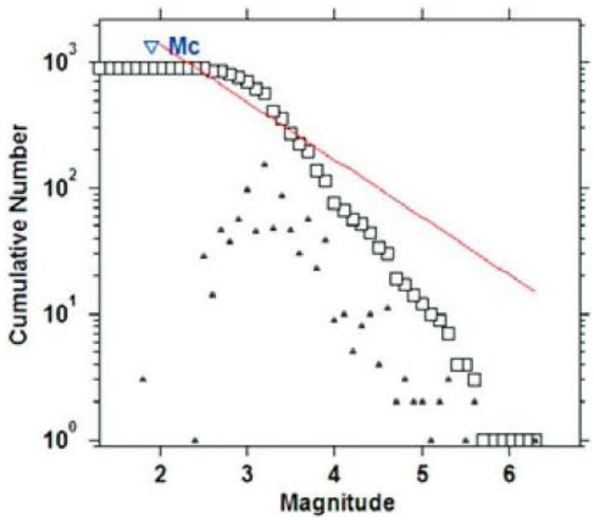
(d)Best combinations



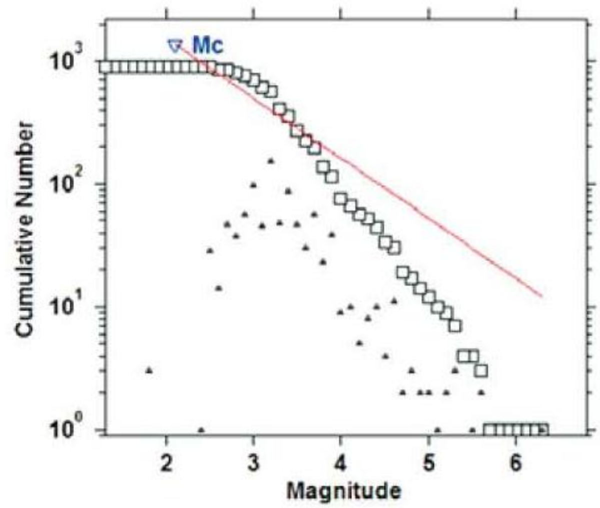
(e) Entire Magnitude Range



(f)Shi and Bolt (1982) method



(g)Bootstrap method



(h) Cao and Gao (2002) method

Fig 12.3(a-h): Methods of Recurrence relation estimation

Topic 6

M_{max} Estimation

- The maximum magnitude is an important variable in the seismic hazard estimation as it reflects maximum potential of strain released in larger earthquakes. The instrumental and historical records of earthquakes are often too short to reflect the full potential of faults or thrusts.

- The maximum regional magnitude, M_{max}, is defined as the upper limit of magnitude for a given region or it is magnitude of largest possible earthquake. In other words it is a sharp cut-off magnitude at a maximum magnitude Mmax, so that, by definition, no earthquakes are to be expected with magnitude exceeding Mmax.

- The maximum earthquake magnitude in a given area can be estimated using the geothermal gradient. Such a relation is brought about by the fact that the upper limit of fault size is constrained within the brittle zone in the crust, the thickness of which is regulated by the geothermal structure of the focal region.

- An expected maximum magnitude value is widely needed where the disaster prevention planning and the earthquake-proof design for buildings are ongoing.

- The probabilistic approach for estimating the maximum regional magnitude Mmax was suggested by Kijko and Sellevoll (1989) based on the doubly truncated G-R relationship. It has been further refined by Kijko and Graham (1998) to consider the uncertainties in the input magnitude data. Mmax from Kijko-Sellevoll-Bayes estimator is obtained as a solution of following equation, Kijko and Graham (1998)

$$m_{max} = \frac{m_{max}^{obs} + \partial^{1/q+2} \exp[nr^{q}/(1-r^{q})}{\beta}[\Gamma(-1/q, \partial r^{q}) - \Gamma(-1/q, \partial)] \qquad (12.16)$$

where $p = \bar{\beta}/(\sigma_{\beta})^2$, $q = (\bar{\beta}/\sigma_{\beta})^2$, where β = 2.303b, $\bar{\beta}$ denotes the mean value of β, σ_{β} is the standard deviation of β and Cβ is a normalizing coefficient and which is equal to {1−[p/(p+mmax−mmin)]q}−1, r = p/(p + mmax − mmin), c1 = exp[−n(1 − Cβ)], δ = nCβ and Γ(·, ·) is the Incomplete Gamma Function. Mmax is obtained by iterative solution of equation (14). The results showing the values of λ, β and Mmax are given in table 2. The recurrence period and probability of occurrence of magnitude 6.0 earthquakes in 50 years and 100 years in the respective source zones are shown in table 3 for all the three catalogues.

Topic 7

Predictive relationships

- R3 in the Figure 12.1 represents the best distance measure for peak amplitude predictive relationships. It is the distance to the zone of highest energy release. Predictive relationships for earthquake ground motion and response spectral values are empirically obtained by well-designed regression analyses of a particular strong-motion parameter data set.

- Predictive relationship allows the estimation of the peak ground motions at a given distance and for an assumed magnitude. Thus, ground motions are estimated for a given magnitude earthquake, and at a particular distance from the assumed fault, in a manner consistent with recordings of past earthquakes under similar conditions.

- Recently, Bommer et al. (2003) analyzed a number of strong-motion predictive relationships and proposed a simple method to scale any such relation according to style-of-faulting.

- Predictive relationships usually express gorund motion parameters as functions of magnitude, distance and in some cases, other variables for example,

$$Y = f(M, R, P_i) \qquad (12.17)$$

- Where Y is the ground motion parameter of interest, M the magnitude of the earthquake, R a measure of the distance form the source to the site being considered, and the Pi are other parameters which may be used to characterize the earthquake source, wave propagation path, and/or local site conditions.

- Common forms for predictive relationships are based on the following observations:

    1. Peak values of strong motion parameters are approximately lognormally distributed. As a result, the regression is usually performed on the logarithm of Y rather than on Y itself.
    2. Earthquake magnitude is typically defined as the logarithm of some peak motion parameter. Consequently, ln Y should be approximately proportional to M.
    3. The spreading of stress waves as they travel away from the source of an earthquake causes body wave amplitudes to decrease according to $1/R$ and surface wave amplitudes to decrease according to $1/\sqrt{R}$.
    4. The area over which fault rupture occurs increases with increasing earthquake magnitude. As a result, some of the waves that produce strong motion at a site arrive from a distance, R, and some arrive from greater distances. The effective distance, therefore, is greater than R by an amount that increases with increasing magnitude.
    5. Some of the energy carried by stress waves is absorbed by the materials they travel through. This material damping causes ground motion amplitudes to decrease exponentially with R.
    6. Ground motion parameters may be influenced by source characteristics or site characteristics.

- Combining these observations, a typical predictive relationship may have the form

$$\underbrace{\ln Y}_{1} = \underbrace{C_1 + C_2 M + C_3 M^{C4}}_{2} + \underbrace{C_5 \ln[R}_{3} + \underbrace{C_6 \exp(C_7 M)]}_{4} + \underbrace{C_8 R}_{5} + \underbrace{f(\text{source}) + f(\text{site})}_{6} . \sigma_{\ln Y} = C_9 \qquad (12.18)$$

- Where the circled numbers indicate the observations associated with each term. Some predictive relationships utilize all these terms and others do not.

Topic 8

Deterministic Seismic Hazard Analysis

- Earliest approach taken to seismic hazard analysis Originated in nuclear power industry applications Still used for some significant structures such as:

  1. Nuclear power plants
  2. Large dams
  3. Large bridges
  4. Hazardous waste containment facilities
  5. As "cap" for probabilistic analyses

- In Deterministic Seismic Hazard Analysis (DSHA), is done for a particular earthquake, either assumed or realistic. The DSHA approach uses the known seismic sources sufficiently near the site and available historical seismic and geological data to generate discrete, single-valued events or models of ground motion at the site. Typically one or more earthquakes are specified by magnitude and location with respect to the site. Usually the earthquakes are assumed to occur on the portion of the site closest to the site. The site ground motions are estimated deterministically, given the magnitude, source-to-site distance, and site condition.

- Deterministic Seismic Hazard Analysis Consists of four primary steps:

  1. Identification and characterization of all sources
  2. Selection of source-site distance parameter
  3. Selection of "controlling earthquake".
  4. Definition of hazard using controlling earthquake

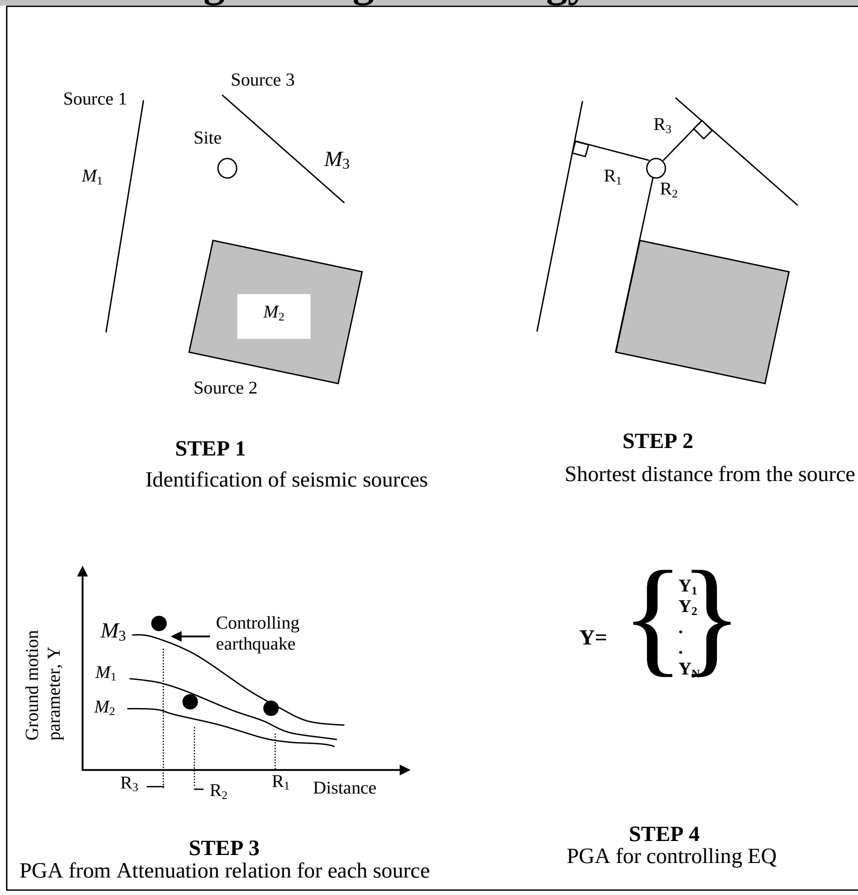
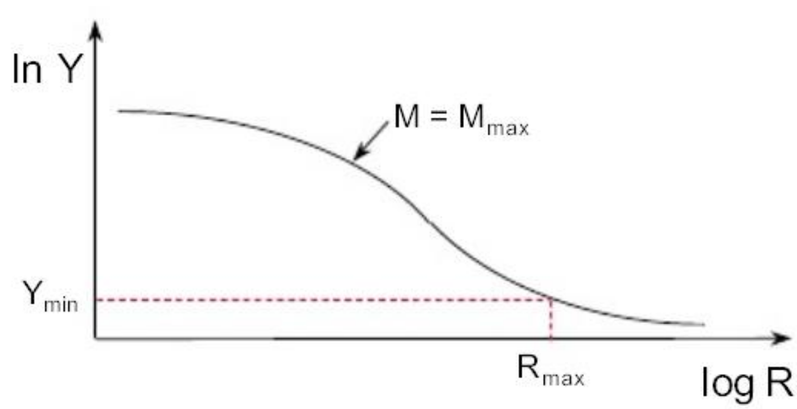


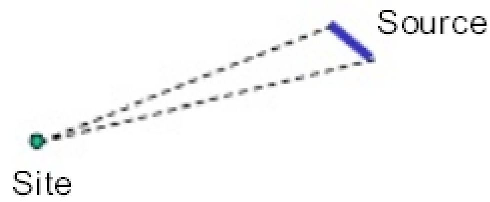
Fig 12.4.: Four Steps of a deterministic seismic hazard analysis

- **Step 1**: Identification of all sources capable of producing significant ground motion at the site such as Large sources at long distances and Small sources at short distances. Characterization includes Definition of source geometry and Establishment of earthquake potential.
- Estimate maximum magnitude that could be produced by any source in vicinity of site and Find value of Rmax - corresponds to Mmax at threshold value of parameter of interest, Ymin.

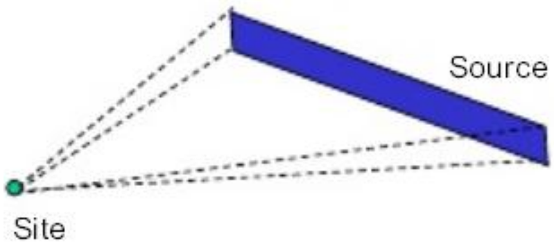


- Definition of source geometry includes

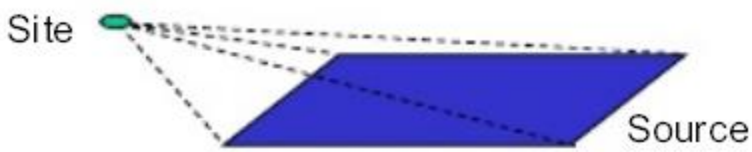
    1. Point source where there is constant source- to site distance. Earthquakes associated with volcanic activity, for example, generally originate in zones near the volcanoes that are small enough to allow them to be characterized as point source.



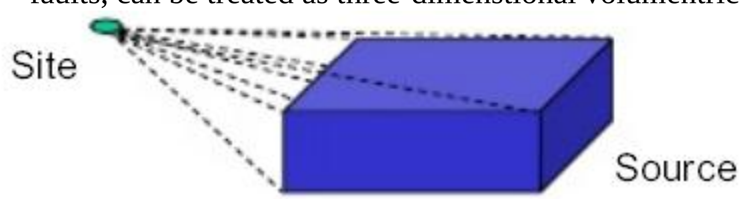
    2. Linear source in which one parameter controls distance example Shallow and distant fault



    3. Areal source in which two geometric parameters control distance example Constant depth crustal source. Well defined fault planes, on which earthquakes can occur at many different locations, can be considered as two-dimentional areal sources.



    4. Areas where earthquake mechanisms are poorly defined, or where faulting is so extensive as to preclude distinction between individual faults, can be treated as three-dimenstional volumentric sources



- Establish earthquake potential - typically Mmax can be found by the following

1. Empirical correlations
    a. Rupture length correlations
    b. Rupture area correlations
    c. Maximum surface displacement correlations

2. "Theoretical" determination by Slip rate correlations

- Slip rate approach: seismic moment is given by the following equation, where μ= shear modulus of rock, A = rupture area, D = average displacement over rupture area

$$M_0 = \mu AD \qquad (12.19)$$

- Slip rate (S) approach: If average displacement relieves stress/strain built up by movement of the plates over some period, T, then

$$D = S.T \qquad (12.20)$$

- Then the "moment rate" can be defined as

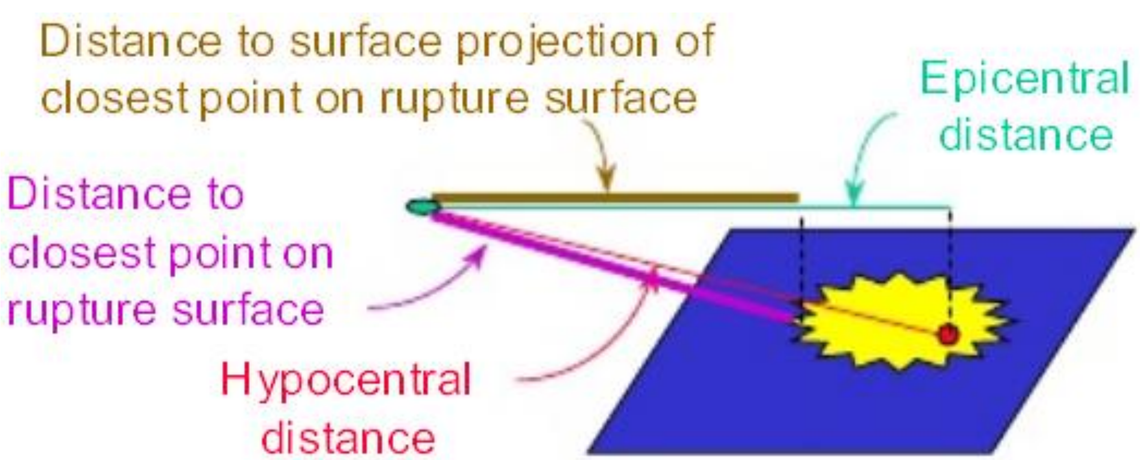
$$M_0 = M_0/T = \mu AS \qquad (12.21)$$

- Knowing the slip rate and knowing (assuming) values of m, A, and T, the moment rate can be used to estimate the seismic moment as

$$M_0 = M_0.T \qquad (12.22)$$

$$Mw = \log M_0/1.5 - 10.7 \qquad (12.23)$$

- **Step 2:** Selection of source-site distance parameter must be consistent with predictive relationship and should include finite fault effect (Figs 15.5-15.7)



Source – Site Distance

- Measurement of Distances

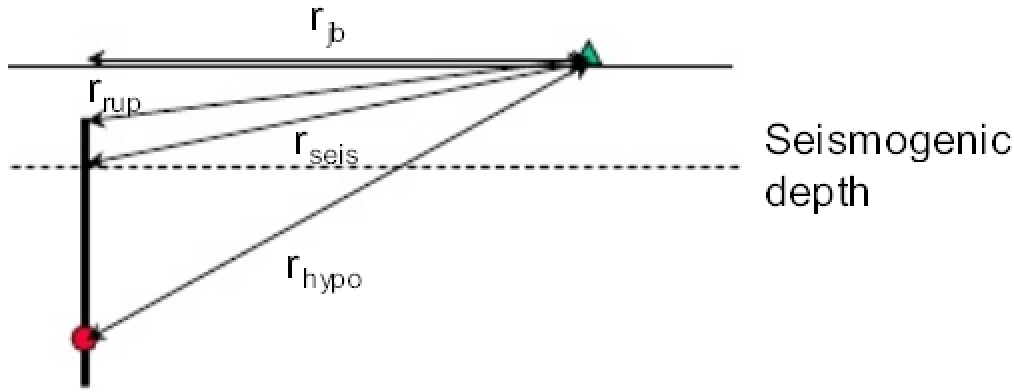


Fig 12.5: Vertical Faults

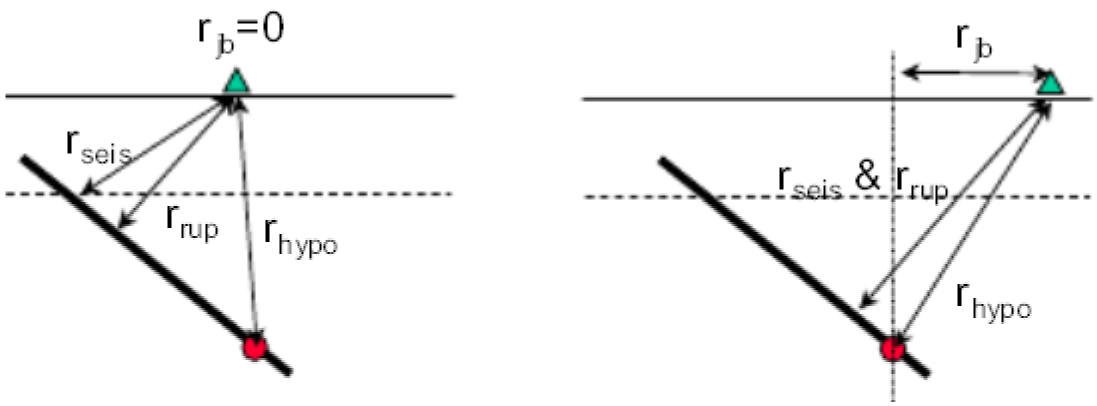
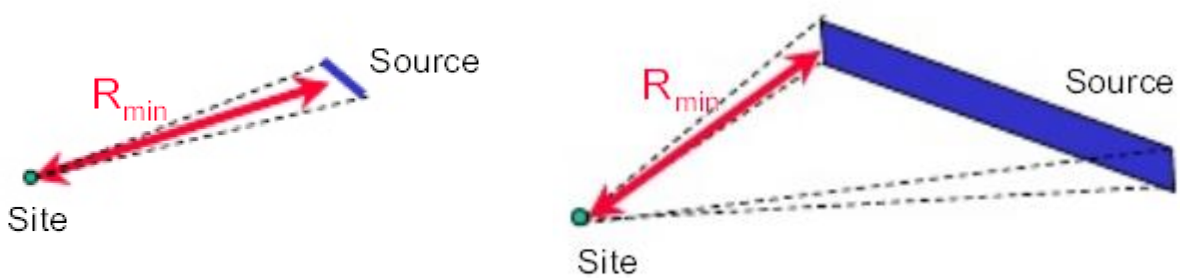
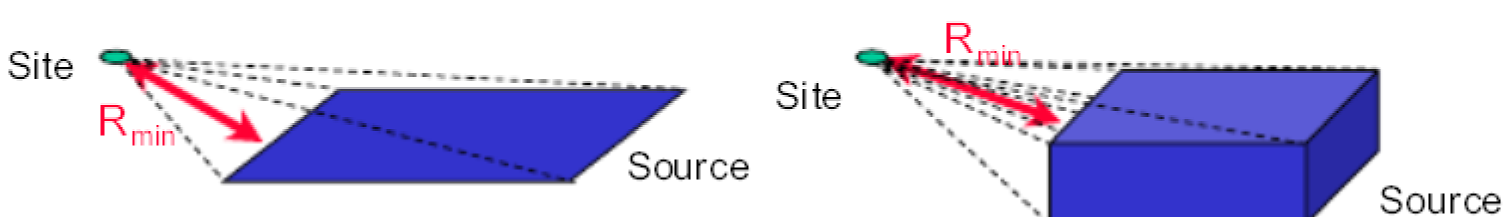


Fig 12.6: Dipping Faults

- Typically assume shortest source-site distance for Point Source, Linear source, Areal source and Volumetric source



Point Source **Linear source**



Areal source

Fig 12.7: Arial sources and associated distances

- **Step 3:** Selection of Controlling Earthquakes is based on ground motion parameter(s). Consider all sources, assume Mmax occurs at Rmin for each source Compute ground motion parameter(s) based on Mmax and Rmin Determine critical value(s) of ground motion parameter(s). An example is shown in Figure 12.8 below.

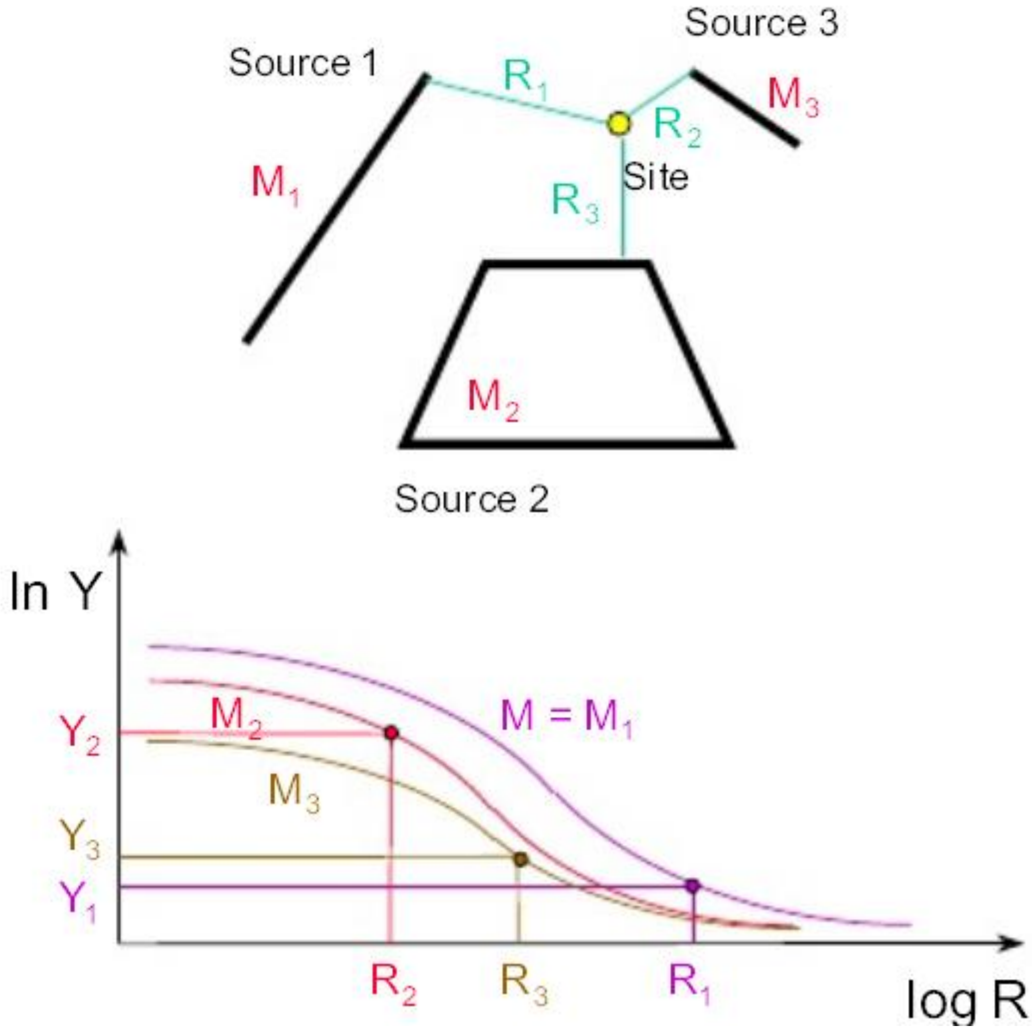


Fig 12.8: Selection of Controlling Earthquake (Combination of M_2 and R_2 produces highest value of Y)

- **Step 4:** Definition of hazard using controlling earthquake involves the use of M and R to determine parameters such as Peak acceleration, spectral acceleration and Duration.

- DSHA calculations are relatively simple, but implementation of procedure in practice involves numerous difficult judgments. The lack of explicit consideration of uncertainties should not be taken to imply that those uncertainties do not exist.

- Typical results obtained from DSHA analysis is shown in Figure 12.9

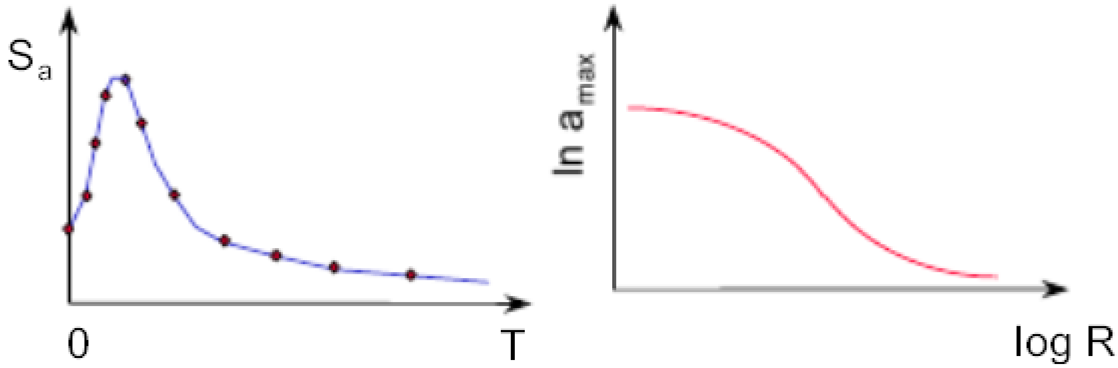


Fig 12.9: Typical spectral curve and hazard plot from DSHA analysis

Topic 9

Probabilistic Seismic Hazard Analysis

- The seeds of PSHA were sown in the early 1960s in the form of two efforts that came together in 1966. One effort was the 1964 doctoral dissertation of Allin Cornell at Stanford titled 'Stochastic Processes in Civil Engineering,' which studied probability distributions of factors affecting engineering decisions.

- The second effort consisted of studies at the Universidad National Autonomy de Mexico (UNAM) by PhD student Luis Esteva, Prof. Emilio Rosenblueth, and co-workers, who were studying earthquake ground motions, their dependence on magnitude and distance, and the relationship between the frequency of occurrence of earthquakes and the frequency of occurrence of ground motions at a site.

- Probabilistic seismic hazard analysis (PSHA) is the most widely used approach for the determination of seismic design loads for engineering structures. The use of probabilistic concept has allowed uncertainties in the size, location, and rate of recurrence of earthquakes and in the variation of ground motion characteristics with earthquake size and location to be explicitly considered for the evaluation of seismic hazard. In addition, PSHA provides a frame work in which these uncertainties can be identified, quantified and combined in a rational manner to provide a more complete picture of the seismic hazard.

- Figure 12.10 shows element of probabilistic hazard methodology

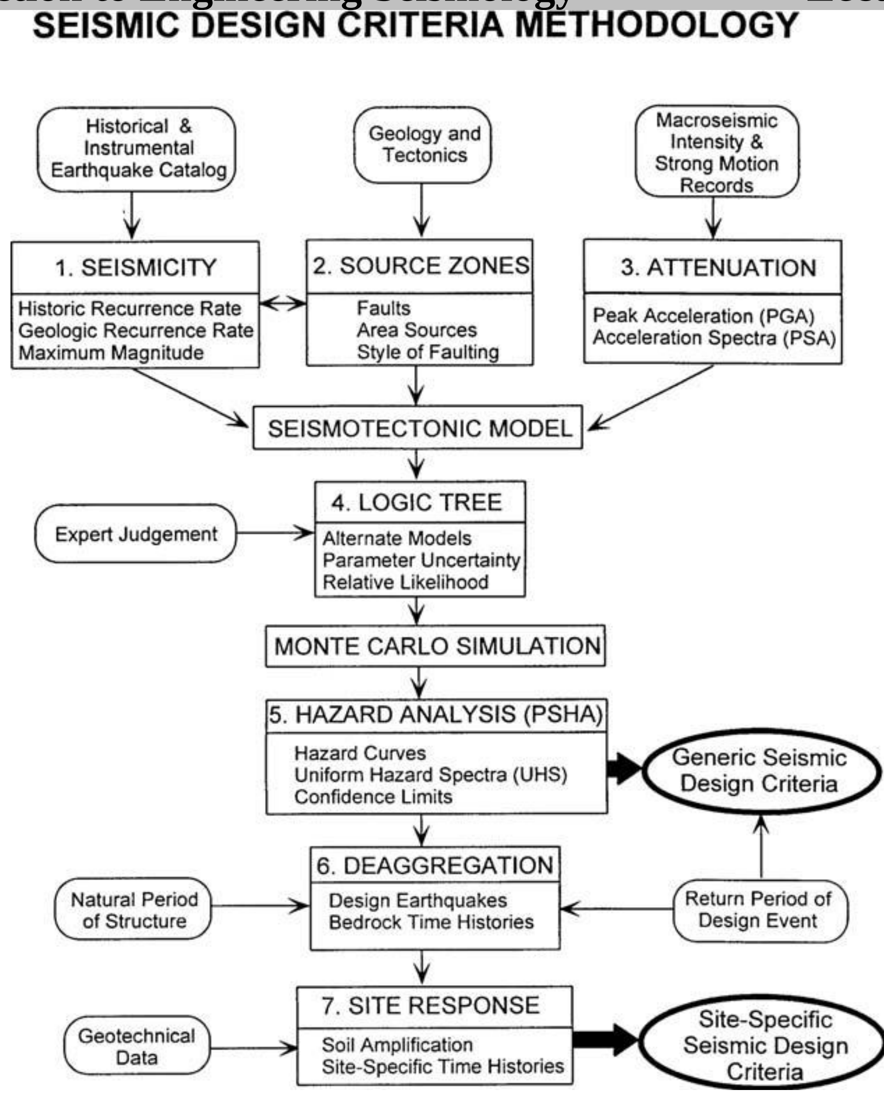


Fig 12.10: Flowchart showing the elements of the probabilistic hazard methodology in the context of a seismic design criteria methodology.

Topic 10

Applicability of DSHA and PSHA

- DSHA involve the assumption of some scenario and the occurrence of an earthquake of a particular size at a particular location for which ground motion characteristics are determined.

- When applied to structures for which failure could have catastrophic consequences, such as nuclear power plants and large dams, DSHA provides a straight forward framework for evaluation of “worst-case” ground motions.

- However, it provides no information on the likelihood of occurrence of the controlling earthquake, the likelihood of it occurring where it is assumed to occur, the level of shaking that might be expected during a finite period of time (such as the useful lifetime of a particular structure or facility), or the effects of uncertainties in the various steps required to compute the resulting ground motion characteristics.

- PSHA allows uncertainties in the size, location, rate of recurrence, and effects of earthquakes to be explicitly considered in the evaluation of seismic hazards. A PSHA requires that uncertainties in earthquake location, size, recurrence, and ground shaking effects be quantified.

- The accuracy of PSHA depends on the accuracy with which uncertainty in earthquake size, location, recurrence, and effects can be characterized. Although models and procedures for characterization of uncertainty of these parameters are available they may be based on data collected over periods of time that, geologically, are very short. Engineering judgment must be applied to the interpretation of PSHA results.

- Model uncertainties can be incorporated into a PSHA by means a of a logic tree, eg. Fig 12.13. A logic tree allows the use of alternative models, each of which is assigned a weighting factor related to the likelihood of that model being correct. The weighting factors are usually assigned subjectively, often using expert opinion.

Topic 11

Summary of uncertainties

- **Location or Spatial Uncertainty-** Earthquakes are usually assumed to be uniformly distributed within a particular source zone. A uniform distribution within the source zone does not, however, often translate into a uniform distribution of source-to-site distance.

- Since predictive relationships express ground motion parameters in terms of some measure of source-to-site distance, the spatial uncertainty must be described with respect to the appropriate distance parameter. The uncertainty in source-to-site distance can be described by a probability density function.

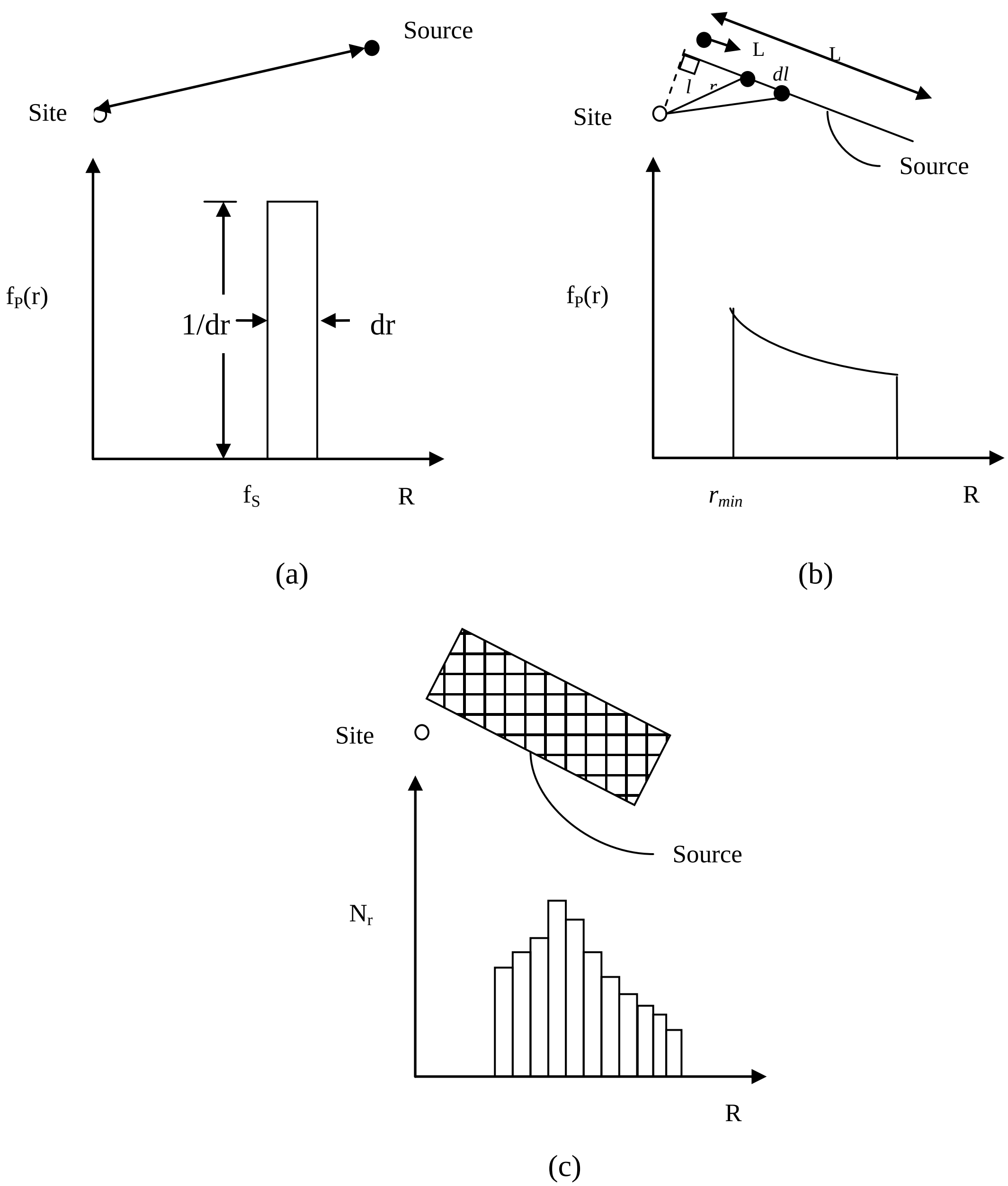


Fig 12.11: Examples of Variation of Source to Site Distance for different source zone geometries.

- For the point source of figure 12.11(a) the distance R, is known to be r_S; consequently, the probability that $R = r_s$ is assumed to be 1 and the probability that $R \neq r_S$, zero. For the linear source of figure 12.11(b), the probability that an earthquake occurs on the small segment of the fault between L=l and L=l+dl is the same as the probability that it occurs between R = r and R = r+dr; that is,

$$f_L(l)dl = f_R(r)dr \qquad (12.24)$$

- Where $f_L(l)$ and $f_R(r)$ are the probability density functions for the variables L and R, respectively. Consequently,

$$f_R(r) = f_L(l)\frac{dl}{dr} \tag{12.25}$$

- If earthquakes are assumed to be uniformly distributed over the length of the fault, $f_L(l) = l / L_f$ since $l^2 = r^2 - r_{min}^2$ the probability density function of R is given by

$$f_R(r) = \frac{r}{L_f\sqrt{r^2 - r^2_{min}}} \tag{12.26}$$

- **Size uncertainty**- all source zones have a maximum earthquake magnitude that cannot be exceeded; in general, the source zone will produce earthquakes of different sizes up to the maximum earthquake, with smaller earthquakes occurring more frequently than larger ones.

- The strain energy may be released aseismically, or in the form of earthquakes. Assuming that the strain energy is released by earthquakes of magnitude 5.5 to 9.0 and that the average fault displacement is one-half the maximum surface displacement the rate of movement was related to earthquake magnitude and recurrence interval.

- The distribution of earthquake sizes in a given period of time is described by recurrence laws such as: Gutenberg-Richter Recurrence law, Bounded Gutenberg-Richter Recurrence laws, Characteristic Earthquake Recurrence Laws and other Recurrence Laws.

- A basic assumption of PSHA is that the recurrence law obtained from past seismicity is appropriate for the prediction of future seismicity. In most PSHA's, the lower threshold magnitude is set at values from about 4.0 to 5.0 since magnitudes smaller than that seldom cause significant damage. The resulting probability distribution of magnitude for the Gutenberg-Richter law with lower bound can be expressed in terms of the cumulative distribution function (CDF)

$$F_M(m) = P[M < m \mid M > m_0] = \frac{\lambda_{m_0} - \lambda_m}{\lambda_{m_0}} = 1 - e^{-\beta(m-m_0)} \tag{12.27}$$

- Or the probability density function (PDF):

$$P_M(m) = \frac{\beta e^{-\beta(m-m_0)}}{1-\beta e^{-\beta(m_u-m_0)}};\ (m_0 \le m \le m_u),\ \beta = 2.303b \tag{12.28}$$

- **Effect Uncertainty**: seismic hazard or effects can be expressed in the form of seismic hazard curves and can be obtained for individual source zones and combined to express the aggregate hazard at a particular site.

- The probability of exceeding a particular value of y*, of a ground motion parameter, Y, is calculated for one possible earthquake at one possible source location and then multiplied by the probability that, that particular magnitude earthquake would occur at that particular location. The process is then repeated for all possible magnitudes and locations with the probabilities of each summed.

- For a given earthquake occurrence, the probability that a ground motion parameter Y will exceed a particular value y* can be computed using the total probability theorem, that is,

$$P[Y > y^*] = P[Y > y^* \mid X]P[X] = \int P[Y > y^* \mid X] f_x(X)dx \qquad (12.29)$$

- Where X is a vector of random variables that influence Y. In most cases the quantities in X are limited to the magnitude, M, and distance, R. assuming that M and R are independent, the probability of exceedance can be written as

$$P[Y > y^*] = \iint P[Y > y^* \mid m, r] f_M(m) f_R(r) dm.dr \qquad (12.30)$$

- Where P[Y>y*|m, r] is obtained from the predictive relationship and $f_M(m)$ and $f_R(r)$ are the probability density functions for magnitude and distance, respectively.

- If the site of interest is in a region of Ns potential earthquake sources, each of which has an average rate of threshold magnitude exceedance, $v_i = [\exp(\alpha_i - \beta_i m_0)]$, the total average exceedance rate for the region will be given by

$$\lambda_{y^*} = \sum_{i=1}^{N_S} v_i \iint P[Y > y^* \mid m, r] f_{Mi}(m) f_{Ri}(r) dm.dr \qquad (12.31)$$

- The individual components of above equation are, for virtually all realistic PSHA's, sufficiently complicated that the integrals cannot be evaluated analytically. Numerical integration, which can be performed by a variety of different techniques, is therefore required.

- The next step is to divide the possible ranges of magnitude and distance into N_M and N_R segments, respectively the average exceedance rate can then be estimated by

$$\lambda_{y^*} = \sum_{i=1}^{N_S}\sum_{j=1}^{N_M}\sum_{k=1}^{N_R} v_i P[Y > y^* \mid m_j, r_k] f_{Mi}(m_j) f_{Ri}(r_k) dm.dr \qquad (12.32)$$

- Where $m_j = m_0 + (j - 0.5)(m_{\max} - m_0)/N_M$, $r_k = r_{\min} + (k - 0.5)(r_{\max} - r_{\min})/N_R$, $\Delta_m = (m_{\max} - m_0)/N_m$, and $\Delta r = (r_{\max} - r_{\min})/N_R$. This is equivalent to assuming that each source is capable of generating only N_M different earthquakes of magnitude, m_j, at only N_R different source-to-site distances, r_k. Then the above equation is equivalent to

$$\lambda_{y^*} = \sum_{i=1}^{N_S}\sum_{j=1}^{N_M}\sum_{k=1}^{N_R} v_i P[Y > y^* \mid m_j, r_k] P[M = m_j] P[R = r_k] \qquad (12.33)$$

- The accuracy of the crude numerical integration procedure described above increases with increasing N_M and N_R. More refined methods of numerical integration will provide greater accuracy at the same values of N_M and N_R.

- **Temporal Uncertainty**: the temporal occurrence of earthquakes is most commonly described by a Poisson model. The Poisson model provides a simple framework for evaluating probabilities of events that follow a Poisson process, one that yields values of a random variable describing the number of occurrences of a particular event during a given time interval or in a specified spatial region.

- Since PSHA's deals with temporal uncertainty, the spatial applications of the Poisson model will not be considered further. Poisson processes possess the following properties, which indicate that the events of a Poisson process occur randomly, with no "memory" of the time, size or location of any preceding event.

    1. The number of occurrences in one time interval are independent of the number that occur in any other time interval
    2. The probability of occurrence during a very short time interval is proportional to the length of the time interval
    3. The probability of more than one occurrence during a very short time interval is negligible.

- For a Poisson process, the probability of a random variable N, representing the number of occurrences of a particular event during a given time interval is given by

$$P[N = n] = \frac{\mu_n . e^{-\mu}}{n!} \tag{12.33}$$

- Where μ is the average number of occurrences of the event in that time interval. The time between events in a Poisson process can be shown to be exponentially distributed. To characterize the temporal distribution of earthquake recurrence for PSHA purposes, the Poisson probability is usually expressed as

$$P[N = n] = \frac{(\lambda t)^n . e^{-\lambda t}}{n!} \tag{12.34}$$

- Where λ the average rate of occurrence of the event and t is the time period of interest. Note that the probability of occurrence of at least one event in a period of time t is given by

$$P[N \geq 1] = P[N = 1] + P[N = 2] + P[N = 3] + ... + P[N = \infty] = 1 - P[N = 0] = 1 - e^{-\lambda t} \tag{12.35}$$

- When the event of interest is the exceedance of a particular earthquake magnitude, the Poisson model can be combined with a suitable recurrence law to predict the probability of at least one exceedance in a period of t years by the expression

$$P[N \geq 1] = 1 - e^{-\lambda_m t} \tag{12.36}$$

- Poisson model is useful for practical seismic risk analysis except when the seismic hazard is dominated by a single source for which the time interval since the previous significant event is greater than the average interevent time and when the source displays strong “characteristic-time” behavior.

Topic 12

Uncertainty in the Hypocentral Distance

- On an active fault it is possible that all points are equally vulnerable to rupture. Thus, depending on the relative orientation of a fault with respect to the station, the hypocentral distance R will have to be treated as a random variable. Further, the conditional probability distribution function of R given that the magnitude M= m for a rupture segment, uniformly distributed along a fault is given by

$$P(R < r \mid M = m) = 0 \text{ for } R < (D^2 + L_0^2)^{1/2} \quad (12.37)$$

$$P(R < r \mid M = m) = \frac{(r^2 - d^2)^{1/2} - L_0}{L - X(m)} \text{ for} \quad (12.38)$$

$$(D^2 + L_0^2) \le R < \left[D^2 + (L + L_0 - X(m))^2\right]^{1/2}$$

Here, *X(m)* the rupture length in kilometres, for an event of magnitude *m* is given by

$$X(m) = \text{MIN}\left[10^{(-2.44+0.59m)}, \text{faultlength}\right] \quad (12.39)$$

- MIN stands for the minimum of the two arguments inside the parentheses. This condition is used to confine the rupture to the fault length. The first term provides an estimate of the rupture length expected for an event of magnitude *m*.

- The above solution pertains to the case of a fault situated entirely to one side of a site. In the more general situation when the fault is extending on both sides of the source, the conditional probabilities for the two sides are multiplied by the fraction of length of the corresponding sides and summed up to get the probability for the total fault.

Topic 13

Regional Recurrence

- Each seismic source has a maximum earthquake that cannot exceed. In PSHA, the lower magnitude can be taken from 4.0 to 5.0 magnitudes, since smaller than this will not cause significant damage to the engineering structures and larger magnitude can be evaluated by considering the seismotectonic of the region and historic earthquake data.

- The magnitude recurrence model for a seismic source specifies the frequency of seismic events of various sizes per year. For any region the seismic parameters are determined using Gutenberg-Richter (G-R) magnitude-frequency relationship which is given in Equation below.

- The recurrence relation of each fault capable of producing earthquake magnitude in the range m^0 to m^u is calculated using the truncated exponential recurrence model developed by Cornel and Van Mark (1969), and it is given by the following expression:

$$N(m) = N_i(m_0)\frac{\beta e^{-\beta(m-m^0)}}{1-e^{-\beta(m^u-m^0)}} \tag{12.40}$$

- For $m^0 \leq m < m^u$ Where β=b ln (10) and Ni (m_0) is proposal weightage factor for particular source based on the deaggregation.

Topic 14

Uniform hazard spectrum (UHS)

- The uniform hazard spectra (UHS) are derived from a probabilistic hazard analysis. The basic steps of the analysis are as follows. First, seismotectonic information is used to define seismic source zones. Generally, a number of alternative hypotheses regarding the configuration of these seismic zones are formulated.

- For each source zone, the earthquake catalogue is used to define the magnitude recurrence relation and its uncertainty, which provides the description of the frequency of occurrence of events within the zone, as a function of earthquake magnitude. Ground motion relations are then defined to provide the link between the occurrence of earthquakes within the zones, and the resulting ground motions at a specified location. Ground motion relations can be given in terms of peak ground acceleration or velocity or in terms of response spectral ordinates of specific periods of vibration.

- The final step of the hazard analysis is integration over all earthquake magnitudes and distances, of the contributions to the probability of exceeding specified ground motion levels at the site of interest. Repeating this process for a number of vibration periods defines the uniform hazard spectrum, which is a response spectrum having a specified probability of exceedance at the particular site.

- The uniform hazard spectrum can be thought of as a composite of the types of earthquakes that contribute most strongly to the hazard at the specified probability level. The shape of a ground motion spectrum and therefore, the response spectrum is strongly dependent upon magnitude and distance. In general, the dominant contributor to the short-period ground motion hazard comes from small-to-moderate earthquakes at close distance, whereas larger earthquakes at greater distance contribute most strongly to the long-period ground motion hazard.

Topic 15

Deaggregation

- The PSHA procedures allow computation of the mean annual rate of exceedance at a particular site based on the aggregate risk from potential earthquakes of many different magnitudes occurring at many different source-to-site distances. The rate of exceedance computed in a PSHA, therefore, is not associated with any particular earthquake magnitude or source-site-distance.

- In some cases, it may be useful to estimate the most likely earthquake magnitude and/or the most likely source-site-distance. These quantities may be used, for example, to select existing ground motion records for response analyses. This process of deaggregation requires that the mean annual rate of exceedance be expressed as a function of magnitude and/or distance. For example, the mean annual rate of exceedance can be expressed as a function of magnitude by

$$\lambda_{y^*}(m_j) = P[M = m_j]\sum_{i=1}^{N_S}\sum_{k=1}^{N_R} v_i P[Y > y^* \mid m_j, r_k] P[R = r_k] \qquad (12.41)$$

- Similarly, the mean annual rate of exceedance can be expressed as a function of source-site distance by

$$\lambda_{y^*}(r_k) = P[R = r_k]\sum_{i=1}^{N_S}\sum_{j=1}^{N_M} v_i P[Y > y^* \mid m_j, r_k] P[M = m_j] \qquad (12.42)$$

- Finally it is possible to compute the mean annual rate of exceedance as functions of both earthquake magnitude and source-site distance i.e.

$$\lambda_{y^*}(m_j, r_k) = P[M = m_j] P[R = r_k]\sum_{i=1}^{N_S} v_i P[Y > y^* \mid m_j, r_k] \qquad (12.43)$$

Topic 16

Logic tree methods

- The probability computations described previously allow systematic consideration of uncertainty in the values of the parameters of a particular seismic hazard model. In some cases, however, the best choices for elements of the seismic hazard model itself may not be clear. The use of logic trees provides a convenient framework for the explicit treatment of model uncertainty.

- The logic tree approach allows the use of alternative models, each of which is assigned a weighting factor that is interpreted as the relative likelihood of that model being correct. It consists of a series of nodes, representing points at which models are specified and branches that represent the different models specified at each node. The sum of the possibility of all branches connect to a given node must be 1.

- The simple logic tree allows uncertainty in selection of models for attenuation, magnitude distribution and maximum magnitude to be considered. In this logic tree, attenuation according to the models of Campbell and Bozorgnia (1994) and Boore et al. (1993) are considered equally likely to be correct, hence each is assigned a relative likelihood of 0.5.

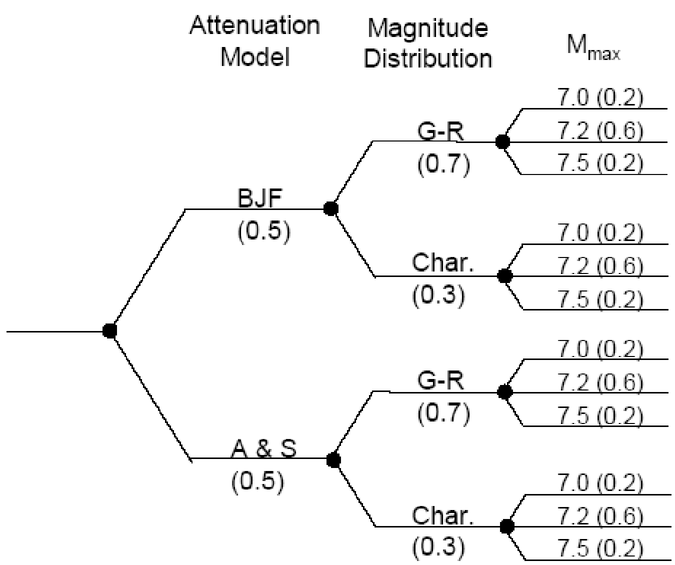


Fig 12.13: Simple logic tree for incorporation of model uncertainty

- Proceeding to the next level of nodes, the Gutenberg-Richter magnitude distribution is considered to be 50% more likely to be correct than the characteristic earthquake distribution.

- At the final level of nodes, different relative likelihoods are assigned to the maximum magnitude. This logic tree terminates with a total of 2x2x3=12 (no. of attenuation models x no. of magnitude distributions x no. of maximum magnitudes) branches (Fig 12.13).

- The relative likelihood of the combination of models and/or parameters implied by each terminal branch is given by the product of the relative likelihood of the terminal branch and all prior branches leading to it. Hence the relative likelihood of the combination of the Campbell attenuation mode, Gutenberg-Richter magnitude distribution and maximum magnitude of 7.5 is 0.5x0.6x0.3=0.09. The sum of the relative likelihoods of the terminal branches or of those at any prior level, is equal to 1.

- To use the logic tree, a seismic hazard analysis is carried out for the combination of models and/or parameters associated with each terminal branch. The result of each analysis is weighted by the relative likelihood of its combination of branches, with the final result taken as the sum of the weighted individual results.

Topic 17

Ready Made Software for PSHA

- PSHA is the most commonly used approach to evaluate the seismic design load for the important engineering projects. PSHA method was initially developed by Cornell (1968) and its computer form was developed by McGuire (1976 and 1978) and Algermissen and Perkins (1976).

- McGuire developed EqRisk in the year 1976 and FRISK in the year 1978. Algermissen and Perkins (1976) developed RISK4a, presently called as SeisRisk III.

- EQRISK, written by McGuire (1976)- The code was freely and widely distributed, and today is still probably the most frequently used hazard software, and has led to PSHA often being referred to as the Cornell-McGuire method.

- The program included the integration across the scatter in the attenuation equation as part of the hazard calculations: "under the principal option for which this program was written, the conditional probability of (random) intensity I exceeding value i at the given site is evaluated using the normal distribution."

- The program commendably made it impossible to run a hazard analysis without sigma by forcing a division by zero if the user attempted to do so. However, the program did, quite naturally, provide the user the option of varying sigma and also acknowledged that it may sometimes even be desired to run hazard calculations without integration across the variability in the ground motions; the user manual (McGuire, 1976) states "SIG is the standard deviation of the residuals about the mean. If no dispersion of residuals is desired, insert a very small value for SIG."

- The importance of EQRISK cannot be overstated because it enabled analysts to begin running PSHA calculations with integration of the scatter fully incorporated, but misunderstanding of the issues resulted in many users approximating the hazard calculations without the scatter by entering very small values of sigma.

Topic 18

Attenuation models

- There is evidence that the decay rate of ground motions is dependent on the magnitude of the causative earthquake (e.g. Douglas, 2003), and the decay rate also changes systematically with distance. Fourier spectra and response spectra moreover decay differently.

- Geometrical spreading is dependent on wave type, where in general body waves spread spherically and surface waves cylindrically, while anelastic attenuation is wavelength (frequency) dependent.

- As hypocentral distance increases, the up going ray impinges at a shallower angle on the interfaces, reflecting increasing amount of energy downwards, thereby reducing the energy transmitted to the surface.

- For moderate and large earthquakes the source can no longer be considered a point source and therefore the size of the fault will mean the decay rate will be less than for smaller events, which is essentially why, for large events, the distance to the causative fault (Joyner-Boore distance) usually is used instead of epicentral or hypocentral distance.

- Assuming the occurrence of an event of magnitude Mi at a site-source distance of Rj, the probability of exceedance of ground motion level Z needs to be defined. From studies of strong-motion records, a lognormal distribution is found to be generally consistent with the data, where the mean often have a simple form such as:

$$\ln Z = C_1 + C_2.M_i + C_3.\ln R_j + C_4.R_j \tag{12.44}$$

- Where Z is the ground motion variable and C1 to C4 are empirically determined constants where C2 reflects magnitude scaling (often in itself magnitude dependent), C3 reflects geometrical spreading and C4 reflects inelastic attenuation. Also found from the recorded data is an estimate of the distribution variance.

- One of the most important sources of uncertainty in PSHA is the variability or scatter in the ground motion (attenuation) models, which is an aleatory uncertainty usually expressed through a sigma (σ) value which is often of the order of 0.3 in natural logarithms, corresponding to about 0.7 in base 10 units. This uncertainty, which usually also is both magnitude and frequency dependent, is mostly expressing a basic randomness in nature and therefore cannot be significantly reduced with more data or knowledge. In PSHA we integrate over this uncertainty which thereby is directly influencing (driving) the seismic hazard results.

Topic 19

Simulation of Strong Ground Motion

- The present earthquake hazard study requires the availability of earthquake ground motion models for peak ground acceleration and spectral acceleration, for the frequency range of engineering interest.

- Available models include near field excitation as well as the attenuation with distance, and the scaling with magnitude here is essentially developed for estimating the effects of an earthquake which is not yet been observed in the region considered.

- Strong-motion attenuation relationships are important in any seismic hazard model along with seismic source characterization, and it is noteworthy here that the uncertainties in attenuation often are among those which contribute the most to the final results. This is true for any area, and in particular for the Himalaya region, where very few strong-motion observations exist in spite of a high seismicity level.

- The empirical Green's function method, developed by Irikura, is applied to synthesize strong ground motion all over the world. Using this method seismologist can explain the nature of the physical phenomena, trying to determine the parameters that describe them and the processes that regulate them.

- Given the spectrum of motion at a site, there are two ways of obtaining ground motions: 1) time-domain simulation and 2) estimates of peak motions using random vibration theory.

Topic 20

Forward modeling in strong ground motion seismology

- Forward modeling deals with the estimation of ground motion at the ground surface by modeling the earthquake faulting process, the earth medium between the earthquake source and the station, and local site effects near the station, such as modeling of topography, basin structure, and soft soil conditions

- For engineering purposes, estimation of ground motion at a location, whether it is the future site of an important engineering facility or the site of a future earthquake, is important. Therefore, forward modeling is used on many occasions for strong ground motion estimation, using the results of inverse modeling as input, if available.

- There are two types of source models: kinematic and dynamic. In kinematic source models the slip over the rupturing portion of a fault, as a function of fault plane coordinates and of time, is known or given a priori (that is, it is not a function of the causative stresses). In dynamic source models, on the other hand, slip over the rupturing segment of a fault is a function of tectonic stresses acting on the region.

- In kinematic source models, the final slip distribution over the fault plane, as well as the location and time-specific evolution of slip over it, can be taken from inverse problem solutions, which use recorded data, or can be found by source models such as Haskell's model.

- In dynamic source models, shear dislocation or slip is the result of a stress drop in a tectonic region [Kostrov and Das, 1989; Scholz, 1989; Madariaga, 1976]. Slip, its amount, direction, the way the rupture travels over the fault plane (i.e., its velocity and direction) are controlled by surrounding forces in the region, as well as by the material properties of the earth material adjacent to the fault plane.

- The rupture of a fault takes between a fraction of a second for small earthquakes and several minutes for major events. During the slippage of the fault, waves are generated, varying from frequencies near zero, corresponding to the permanent ground deformation, up to very high frequencies.

- With the deployment of numerous accelerometers in the near field of causative faults, there has been a definite increase in near-field strong motion data. This has led to an awareness of the existence and importance of coherent, long-period velocity pulses in these regions.

- The 1994 Northridge and 1995 Kobe earthquake strong motion records reconfirmed the severity of the previously noted long-period pulses associated with severe damage. Passing of the rupture front, or so-called source directivity, causes these large, coherent velocity pulses.

- Given this, and the needs of the earthquake engineering community, there is a growing trend towards simulation techniques that incorporate broadband ground motions of longer periods, directivity effects, and higher frequencies.

- For simulation of deterministic ground motion, empirical [e.g., Hartzell, 1978], semi-empirical [e.g., Irikura, 1983; Somerville, 1991], stochastic [e.g., Boore, 1983; Silva et al., 1990], and hybrid methods have been proposed and utilized.

Lecture 12 in Introduction to seismic hazard analysis; methods; Deterministic and probabilistic; suitable method for your project; attenuation models and simulation of strong ground motion