SEISMIC HAZARD ANALYSIS

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SSC – Technical Report (3)

(2003)

SEISMIC HAZARD ANALYSIS

Modern societies and economics depend upon engineered infrastructures supplying externally supplies such as power for their continued successful operation. The supplies and services enable development and growth to proceed and progress. The administration and distribution of the supplies and services are the means by which society operates on a daily basis, and without which the infrastructures of the region would be adversely affected, economically, socially, and politically.

In the foreseeable future, there will be rapid growth of industrial development, increased population, and urban expansion. Experience has demonstrated that natural disaster, and earthquakes in particular have tended to become increasingly destructive since these affect a larger concentration of national properties and population, thus, generating calamitous incidents like the Cairo earthquake: 12 Oct 1992; Yemen earthquake: 28 Dec 1982; Aqabah earthquake: 22 Nov 1995 and Bam earthquake Dec. 2003.

Particularly, three conditions determine the occurrence of an earthquake disaster. The first condition is the magnitude of the earthquake since small seismic events will not sufficiently generate severe ground shaking to cause extensive damage. The second condition is the closeness of the source of earthquakes, but under special conditions, earthquake disaster can occur at further distance (450 km). The third condition is dependent on the degree of earthquake preparedness.

Earthquake hazard depends not only on the seismicity of a region, but also on population density and economic development. Even though seismicity remains constant, both population and economic development are increasing rapidly. Identifying sources of vulnerability and taking steps to mitigate the consequences of future earthquake disaster are the most essential elements of disaster preparedness. Because the existing facilities represent the main earthquake risk, research and performance evaluation have much desire to be done in this critical area.

In order to reduce earthquake hazards in a rational way, it is necessary to have a clear understanding of the phenomena associated with earthquakes and their adverse effects. The key element in coping with earthquake hazard is the ability to assess seismic hazard. To make rational decisions in coping with earthquakes, it is necessary to know the answers to some questions related to:

- **Sources of destructive earthquakes**
- **Locations of earthquake occurrences**
- **Frequency of various size of earthquakes**
- **Nature of the severe ground motion near the source and its attenuation with distance**
- **Influence of local geology and site condition on the severity of ground shaking**
- **Types of earthquake hazards**
- **Main characteristics that define the damage potential of earthquake shaking**

In many areas of the world, the threat to human activities from earthquakes is sufficient to require their careful consideration in the design of structures and facilities. The goal of earthquake-resistant design is to produce a structure or facility that can withstand a certain level of shaking without excessive damage. That level of shaking is described by a design ground motion, which can be characterized by design ground motion parameters. The specification of design ground motion parameter is one of the most difficult and most important problems in structural earthquake engineering.

Much of the difficulty in design ground motion specification results from its unavoidable reliance on subjective decisions that must be made with incomplete or uncertain information.

These decisions largely revolve around the definition of the boundary between acceptable and excessive damage, and uncertainty in the size, time, and location of future earthquakes.

Seismic hazard analyses involve the quantitative estimation of the future occurrence of seismic activity having the potential to cause damages and losses 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.

DETERMINISTIC SEISMIC HAZARD ANALYSIS

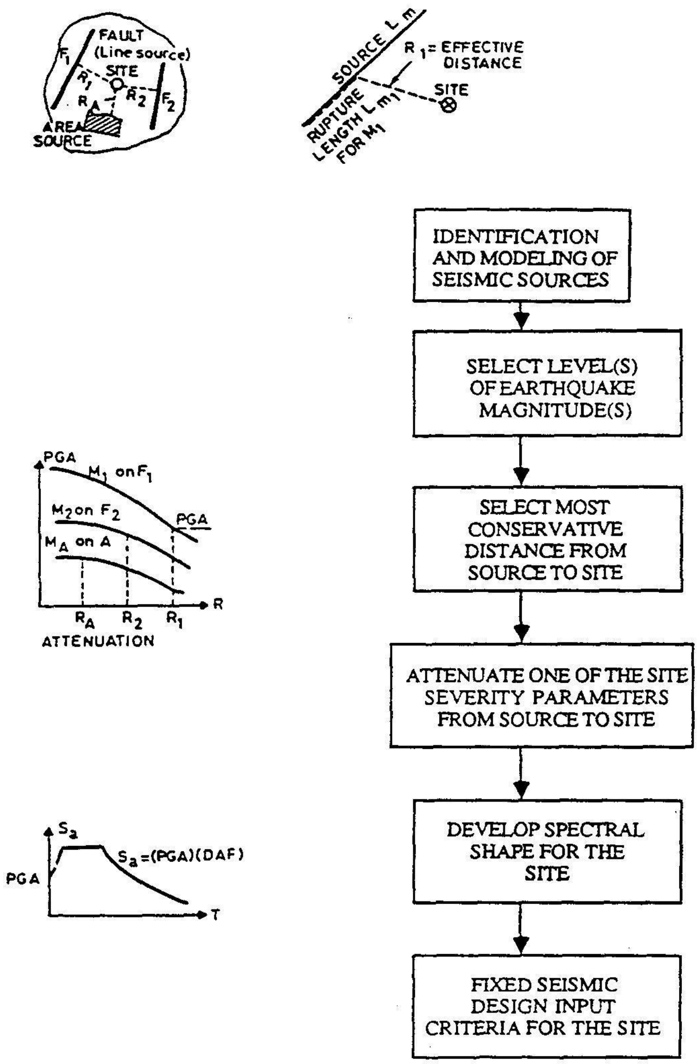
In the early years of geotechnical earthquake engineering, the use of deterministic seismic hazard analysis **(DSHA)** was prevalent. A DSHA involves the development of a particular seismic scenario upon which a ground motion hazard evaluation is based (Reiter, 1990). The scenario consists of the postulated occurrence of an earthquake of a specified size occurring at a specified location. A typical DSHA can be described as a four-step process consisting of :

1. Identification and characterization of all earthquake sources capable of producing significant ground motion at the site. Source characterization includes definition of each source's geometry (the source zone) and earthquake potential.

2. Selection of a source-to-site distance parameter for each source zone. In most DSHAs, the shortest distance between the source zone and the site of interest is selected. The distance may be expressed as an epicentral distance or hypocentrat distance, depending on the measure of distance of the predictive relationship(s) used in the following step.

3. Selection of the controlling earthquake (i.e., the earthquake that is expected to produce the strongest level of shaking), generally expressed in terms of some ground motion parameter, at the site. The selection is made by comparing the levels of shaking produced by earthquakes (identified in step 1) assumed to occur at the distances identified in step 2. The controlling earthquake is described in terms of its size (usually expressed as magnitude) and distance from the site.

4. The hazard at the site is formally defined, usually in terms of the ground motions produced at the site by the controlling earthquake. Peak acceleration, peak velocity, and response spectrum ordinates are commonly used to characterize the seismic hazard.



Schematic Illustration and Flow Chart of Deterministic Seismic Hazard Analysis (DSHA)

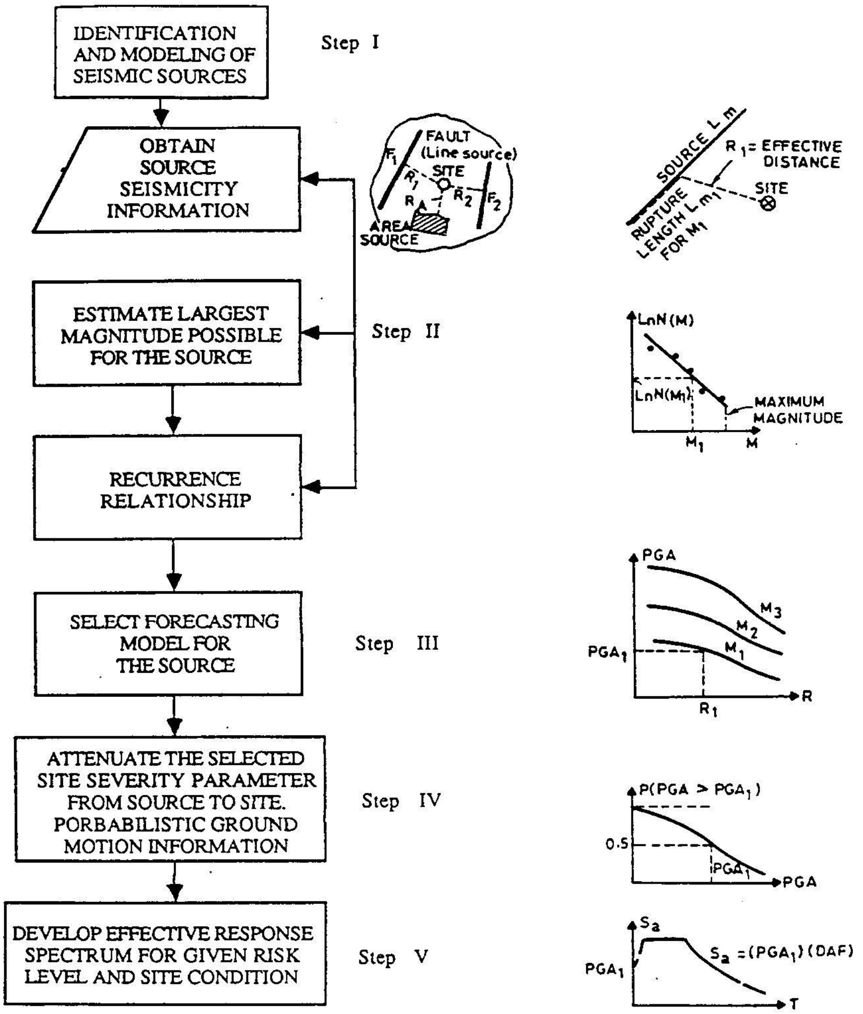
PROBABILISTIC SEISMIC HAZARD ANALYSIS

In the past 20 to 30 years the use of probabilistic concepts 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 in the evaluation of seismic hazards. Probabilistic seismic hazard analysis **(PSHA)** provides a framework in which these uncertainties can be identified, quantified, and combined in a rational manner to provide a more complete picture of the seismic hazard.

The PSHA can also be described as a procedure of four steps each of which bear some degree of similarity to the steps of the DSHA procedure (Reiter, 1990) :

1. The first step, identification and characterization of earthquake sources, is identical to the first step of the DSHA, except that the probability distribution of potential rupture locations within the source must also be characterized. In most cases, uniform probability distributions are assigned to each source zone, implying that earthquakes are equally likely to occur at any point within the source zone. These distributions are then combined with the source geometry to obtain the corresponding probability distribution of source-to-site distance.

2. Next, the seismicity or temporal distribution of earthquake recurrence must be characterized. A recurrence relationship, which specifies the average rate at which an earthquake of some size will be exceeded, is used to characterize the seismicity of each source zone. The recurrence relationship may accommodate the maximum size earthquake, but it does not limit consideration to that earthquake, as DSHAs often do.



Schematic Illustration and Flow C..art of Probabilistic Seismic Hazard Analysis (PSHA)

3. The ground motion produced at the site by earthquakes of any possible size occurring at any possible point in each source zone must be determined with the use of predictive relationships. The uncertainty inherent in the predictive relationship is also considered in a PSHA.

4. Finally, the uncertainties in earthquake location, earthquake size, and ground motion parameter prediction are combined to obtain the probability that the ground motion parameter will be exceeded during a particular time period.

IDENTIFICATION AND EVALUATION OF EARTHQUAKE SOURCES

To evaluate 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. A seismic source is, by definition, the region in the crust of the earth in which future seismicity is assumed to follow a specified probability distribution of occurrence in time, space, and earthquake size. Identification of seismic sources should consider the geologic and tectonic evidence together with the historical and the instrumental seismicity.

Geologic and Tectonic Evidence

The theory of plate tectonics assures us that the occurrence of earthquakes is written in the geologic record, primarily in the form of offsets, or relative displacements, of various strata. Plate tectonics and elastic rebound theory tell us that earthquakes occur to relieve the strain energy that accumulates as plates move relative to each other. The rate of movement, therefore, should be related to the rate of strain energy accumulation and also to the rate of strain energy release (Smith 1976).

The identification of seismic sources from geologic evidence is a vital, though often difficult part of a seismic hazard analysis. The search for geologic evidence of earthquake sources centers on the identification of faults.

Fault Activity

The mere presence of a fault, however, does not indicate the likelihood of future earthquakes. The notion of fault activity is important and has been a topic of considerable discussion and controversy over the years. Although there is general agreement concerning the use of the terms active fault to describe a fault that poses a current earthquake threat and inactive fault to describe one on which past earthquake activity is unlikely to be repeated.

Magnitude Indicators

Geologic evidence can also be used to estimate the magnitude of past earthquakes by correlating observed deformation characteristics with the known magnitudes of recorded earthquakes. Rupture length, rupture area, and fault displacement can be evaluated by post earthquake, field geological investigations. Correlation of magnitude with such quantities involves regression on limited data sets and, consequently, produces an estimate of the expected value of the magnitude.

Historical Seismicity

Earthquake sources may also be identified from records of historical seismicity. The written historical record extends back only a few hundred years or less in the United States; in Japan and the Middle East it may extend about 2000 years and up to 3000 . Historical accounts of ground-shaking effects can be used to confirm the occurrence of past earthquakes and to estimate their geographic distributions of intensity.

Instrumental Seismicity

Over the past 80 or 90 years, about 10 earthquakes of magnitudes > 7 have occurred somewhere in the world each year (Kanamori, 1988). Instrumental records from large earthquakes have been available since about 1900, although many from before 1960 are incomplete or of uneven quality. Nevertheless, instrumental recordings represent the best available information for the identification and evaluation of earthquake sources. Their most significant limitation is the short period of time, compared with the average period of time between large earthquakes, for which they have been available.

EARTHQUAKE SOURCE CHARACTERIZATION

Characterization of an earthquake source requires consideration of the spatial characteristics of the source and of the distribution of earthquakes within that source, of the distribution of earthquake size for each source, and of the distribution of earthquakes with time. Each of these characteristics involves some degree of uncertainty.

Spatial Uncertainty

The geometries of earthquake sources depend on the tectonic processes involved in their formulation. Earthquake 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 sources. Well-defined fault planes, on which earthquakes can occur at many different locations, can be considered as two-dimensional areal sources. 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-dimensional volumetric sources.

Earthquakes are usually assumed to be uniformly distributed within a particular source zone (i.e., earthquakes are considered equally likely to occur at any location). The uncertainty in source-to-site distance can be described by a probability density function.

Size Uncertainty

Once an earthquake source is identified and its corresponding source zone characterized, the seismic hazard analyst's attention is turned toward evaluation of the sizes of earthquakes that the source zone can be expected to produce. All source zones have a maximum earthquake magnitude that cannot be exceeded; it can be large for some and small for others. 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.

Gutenberg and Richter (1944) gathered data from southern California earthquakes over a period of many years and organized the data according to the number of earthquakes that exceeded different magnitudes during that time period. They divided the number of exceedances of each magnitude by the length of the time period to define a mean annual rate of exceedance, $N(m)$ of an earthquake of magnitude m. As would be expected, the mean annual rate of exceedance of small earthquakes is greater than that of large earthquakes. The resulting expression is now known as Gutenberg-Richter law for earthquake recurrence and has the form

$$\mathbf{L_n\, N(m) = \alpha - \beta\, m} \qquad (1)$$

where N(m) is the mean annual rate of exceedance of magnitude, m, α is the mean yearly number of earthquakes of magnitude greater than or equal to zero, and β describes the relative likelihood of large and small earthquakes. As the β value increases, the number of larger magnitude earthquakes decreases compared to those of smaller magnitudes. The α and β parameters are generally obtained by regression on a database of seismicity from the source zone of interest. Eq. (1) may also be expressed as:

$$\mathbf{N(m) = \lambda_m = exp\ (a - \beta\ m)} \qquad \mathbf{(2)}$$

The standard Gutenberg-Richter law covers an infinite range of magnitudes, from -ω to +ω. For engineering purposes, the effects of very small earthquakes are of little interest and it is common to disregard those that are not capable of causing significant damage. If earthquakes smaller than a lower threshold magnitude tn, are eliminated, the mean annual rate of exceedance can be written as:

$$\mathbf{\lambda_m = vexp\ [-\beta\ (m - m_o)] \qquad m > m_o} \qquad \mathbf{(3)}$$

where v = exp(α - β m_o). In most PSHAs, 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 resuling probability distribution of magnitude for the Gutenberg-Richter law with lower bound can be expressed in terms of the cumulative distribution function (CDF):

$$\mathbf{F_M\ (m) = P\ [M < m \backslash M > m_o] = (\lambda_{mo} - \lambda_m)/\ \lambda_{mo} = 1\text{-}exp[-\beta\ (m\text{-}m_o)]} \qquad \mathbf{(4)}$$

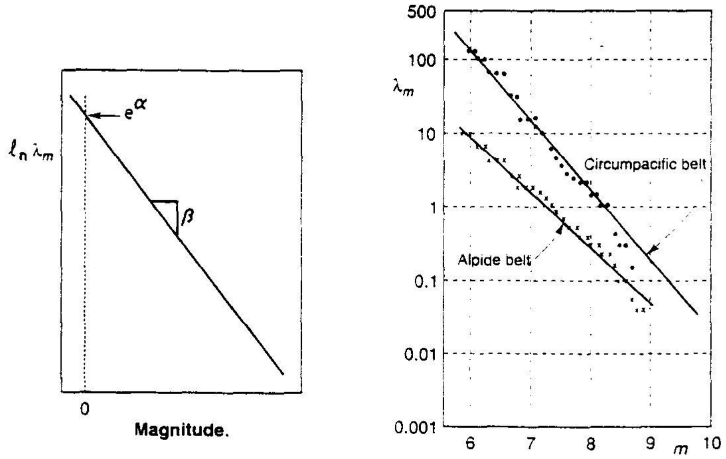
At the other end of the magnitude scale, the standard Gutenberg-Richter law predicts nonzero mean rates of exceedance for magnitudes up to infinity. Some maximum magnitude, $m_{m,,,,}$ is associated with all source zones. If it is known or can be estimated, the mean annual rate of exceedance can be expressed as:

$$\mathbf{\lambda_m = {}_v\frac{exp[-\beta(m - m_o)] - exp[-\beta(m_{max} - m_o)}{1\text{-}\ exp[-\beta\ (m_{max} - m_o)]} \qquad m_o \leq m \leq\ m_{max}} \qquad \mathbf{(5)}$$

The CDF and PDF for the Gutenberg-Richter law with upper and lower bounds can be expressed as:

$$\mathbf{F_M(m) = P[M < m \backslash m_o \leq m_{max}] = 1 - exp[\beta(m\text{-}m_o)]\ /\ 1\text{-}exp[-\beta(m_{max} - m_o)]} \qquad \mathbf{(6)}$$

$$F_M(m) = \frac{\beta \exp[-\beta(m - m_o)]}{1 - \exp[-\beta(m_{max} - m_o)]} \qquad (7)$$



Schematical Illustration of the Gutenberg-Richter Recurrence Law

Temporal Uncertainty

To calculate the probabilities of various hazards occurring in a given time period, the distribution of earthquake occurrence with respect to time must be considered. Earthquakes have long been assumed to occur randomly with time, and in fact, examination of available seismicity records has revealed little evidence (when aftershocks are removed) of temporal patterns in earthquake recurrence.

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. Poisson processes possess the following properties:

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. The properties indicate that the events of a Poisson process occur randomly, with no "memory" of the time, size, or location of any preceding event.

To characterize the temporal distribution of earthquake recurrence for PSHA purposes, the Poisson probability is usually expressed as:

$$P_n(t) = \frac{(\lambda t)^n \exp(-\lambda t)}{n!} \qquad (8)$$

where P,(t) is the probability of having n events in time period t, and X is the average rate of occurrence of the event. Note that the probability of occurrence of at least one event in a period of time t is given by

$$P[N \geq 1, t] = P[N = 1] + P[N = 2] + P[N = 3] + \ldots\ldots$$
$$+ P[N = \omega] = 1 - P(N = 0, t] = 1 - \exp(-\lambda t) \qquad (9)$$

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

$$\mathbf{P\ (at\ least\ one\ M > m\ in\ time\ t) = 1 - exp(-\lambda_m t)} \qquad \mathbf{(10)}$$

It can also be shown that if the arrival of earthquake events follow the Poisson process, then the random description of the time interval between two events follows exponential distribution. Thus,

$$\begin{aligned} \mathbf{f(t)} &= \boldsymbol{\lambda_m} \mathbf{\ exp(-}\boldsymbol{\lambda_m}\mathbf{t)} \qquad \mathbf{t \geq 0} \\ &= \mathbf{0,\ Otherwise} \end{aligned} \qquad \mathbf{(11)}$$

f(t) is the probability distribution function for the inter arrival time, t, between events, and λ_m is the mean rate of occurrence.

If one defines the return period (T_R) as the time interval during which the expected number of occurrences is one, then this much used engineering parameter in risk analysis is obtained as follows: the expected number of events for the Poisson process is given by

$$\mathbf{E(N\ (t)/\ (}\boldsymbol{\lambda_m}\mathbf{) =}\ \boldsymbol{\lambda_m}\mathbf{\ t} \qquad \mathbf{(12)}$$

where E(N(t)/.lm) = Expected number of events for future time t given λ_m

If Eq. (12) is equated to one, we get the definition of return period $\lambda_m T_R = 1$

and hence $\mathbf{T_R = 1/\ }\boldsymbol{\lambda_m}$ **(13)**

T_R is therefore the average time interval between events, and is also the reciprocal of the annual risk of occurrence.

Problem:

The seismicity of a particular region is described by the Gutenberg-Richter recurrence law:

Ln N(m) = 9 – 1.6 m

(a) What is the probability that at least one earthquake of magnitude greater than 7.0 will occur in a 10-year period? In a 50-year period? In a 250-year period?

(b) What is the probability that exactly one earthquake of magnitude greater than 7.0 will occur in a 10-year period? In a 50-year period? In a 250-year period?

(c) Determine the earthquake magnitude that would have a 10% probability of being exceeded at least once in a 50-year period.

Solution :

(a) $\lambda_m = N(m) = \exp(\alpha - \beta m) = \exp(9 - 1.6\ m)$

$\lambda_7 = \exp(9 - 1.6 * 7) = 0.111$ events/year

P(at least one M > 7 in 10 yrs) = 1 - exp(-0.111 * 10) = 67%

The corresponding probabilities in 50 yrs and 250 yrs are 99.6% and 100%, respectively.

(b) $$P_n(t) = \frac{(\lambda_m t)^n \exp(-\lambda_m t)}{n!}$$

$\therefore$

$P_1(10) = 0.111 * 10 \exp(-0.111 * 10) = 36.6\%$

$P_1(50) = 0.111 * 50 \exp(-0.111*50) = 2.2\%$

$P_1(250) = 0.111 * 250 \exp(-0.111 *250) =$ %

(c) P(at least one M > m in 50 yrs) = 0.1

$= 1 - \exp(-\lambda_m *50)$

$\lambda_m = \mathrm{Ln}(1 - 0.1) / 50 = 0.00211$

$\lambda_m = 0.00211 = \exp(9 - 1.6\ m)$

$M = [9 - \mathrm{Ln}(0.00211)] / 1.6 = 9.5$

HAZARD CURVES AT SPECIFIC SITES

PEAK GROUND ACCELERATION AT A SITE

Evaluation of the seismic hazard at sites requires the prediction of the strong ground motion that will be generated by the potentially dangerous earthquakes. If a sufficient number of recordings of strong ground motion at the site (or at other sites with the same source, propagation medium, local geology and topography) is available, then an ensemble of these data can be used to simulate the expected strong ground motion at the site in a so-called "site-specific" manner.

However, for earthquake hazard assessments, where site-specific procedures are not reliable due to lack of strong motion data, either semi-empirical methods or "attenuation relationships" are used. Attenuation relationships which express a convenient parameter of the strong ground motion (usually the Peak Ground Acceleration, PGA) in term of the parameters characterizing the earthquake source, size, propagation medium and the local site geology, are usually utilized.

The selection of the strong motion data for the establishment of the attenuation relationship should consider, (a) the uniformity of the attenuation and source characteristics of the regions

(b) the consistency of the instrumentation and record processing techniques, and

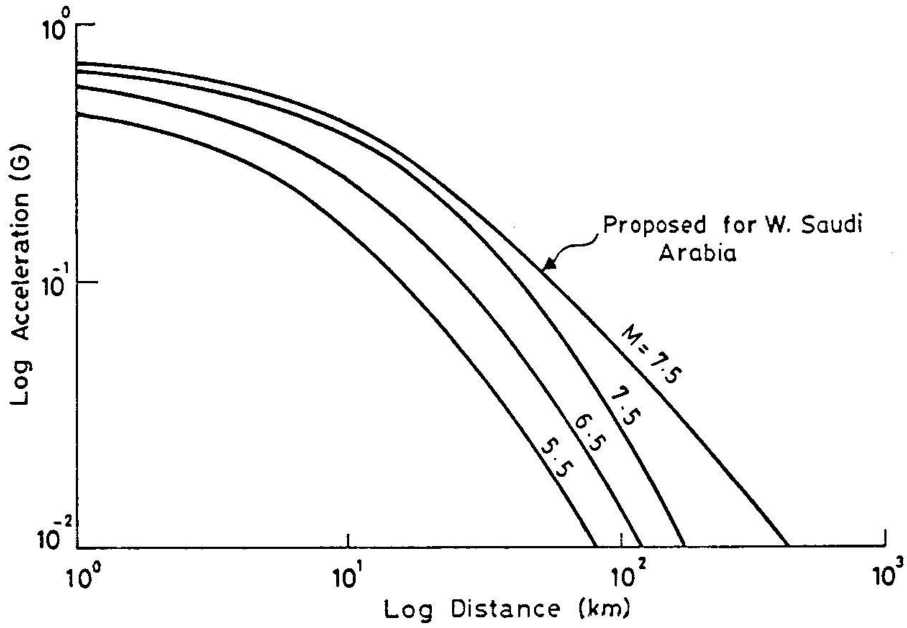
(c) the homogeneous definitions of the strong motion, earthquake, propagation path and the site characteristics.

The general form of the attenuation model used by researchers is given by:

$$\mathbf{Y = b_1 \quad f_1 (M) \quad f_2(R) \quad f_3 (M, R) \; f_4(P_i) \; \varepsilon} \qquad \mathbf{(1)}$$

Where :

Y	is the strong motion parameters to be predicted .
$f_1(M)$	is a function of the magnitude scale M, usually given by the form: $f_1(M) = \exp(b_2 M)$
$f_2(R)$	is a function of the distance R, the most common form being: $f_2 (R) = \exp(b_4 R) (R + b_5)^{-b3}$, where b_3 and b_4 represent respectively the geometric and inelastic attenuation rates.
$f_3(M, R)$	is used to account for the variation of the magnitude scale with the distance, most commonly set equal to unity.
$f_4(P_i)$	is the function representing the earthquake propagation path and site parameters
ε	is a random variable representing the uncertainty in Y.



A Typical Example of Attenuation Relationships

There is a vast number of strong-motion attenuation relationships which have been proposed throughout the years (Lamarra and Shah, 1988). With the advent of the new processing techniques and the availability of more strong motion data the pre-1980 relationships have either become obsolete or have been revised.

Recently, as more strong ground motion data have become available for specific regions, a relationship of the following form has been developed to obtain PGA, which is a special case of Eq. (1).

$$\mathbf{Ln\ A = b_1 + b_2\, M + b_3\ \ Ln\, [\, R + b_4 \exp\, (b_5\, M\,)\,]} \qquad \mathbf{(2)}$$

where b_l through b_5 are constants that jointly depend on the type of seismic source, the transmission path between the source and the site, and the local soil conditions at the site.

Based on 229 peak horizontal accelerations obtained, within 50 km of the rupture zone, from 27 worldwide earthquakes of magnitude 5.0 - 7.7, through 1979, these coefficients were estimated to be:

b_1 = -4.14, b_2 = 0. 868, b_3 = -1. 09, b_4 = 0. 0606, and b_5 = 0. 7

Eq. (2) predicts the median (50 - percentile) peak horizontal acceleration in units of gravity acceleration, g.

Due to the scarcity of strong-motion data in the Kingdom, not much information is available on attenuation of acceleration. However, Eq. (2) was utilized by Thenhaus et al. (1986) representing a region-specific adjustment of the coefficients provided (Thenhaus et al.,1986) for the western region of the Kingdom. The attenuation coefficients suggested by Thenhaus et al., 1986) are:

b_1= -3.303, b_2 = 0.85, b_3 = -1.25, b_4 = 0.087 and b_5 = 0.678.

The standard deviation in LnA appears to be within a range of 0.35 to 0.65 and is generally assumed to hold for all magnitudes and distances of the relation [1].

HAZARD CURVES AT A SITE

Using the attenuation relationship given by Eq. (2), the probability distribution of the Peak Ground Acceleration at a site can be obtained through utilization of a numerical step-by-step procedure (Shah, 1988).

Consider the site (+) and seismic environment around it. R_o and R,, are the nearest and the farthest radial distances from the site to the area source boundaries; M_o and M_u, are the minimum and maximum magnitudes. It is known from the seismic recurrence relationship that the seismic magnitude M will be in the range,

$$\mathbf{M_o < M < M_u ,}$$

and that the attenuation distances will be in the range,

$$\mathbf{R_o < R < R_u ,}$$

Using a numerical analysis approach, the ranges of M and R can be discretized into a convenient number of intervals.

From the seismic recurrence relationship of a source k , the number of occurrences per year which correspond to a magnitude M in the range M; t AM/2 can be computed. Denoting this number by n_{jk} events/year/unit area, it can be calculated as:

$$\mathbf{n_{jk} = N_k (M_j - \Delta M/ 2) - N_k (M_j + \Delta M/ 2)} \qquad \mathbf{(3)}$$

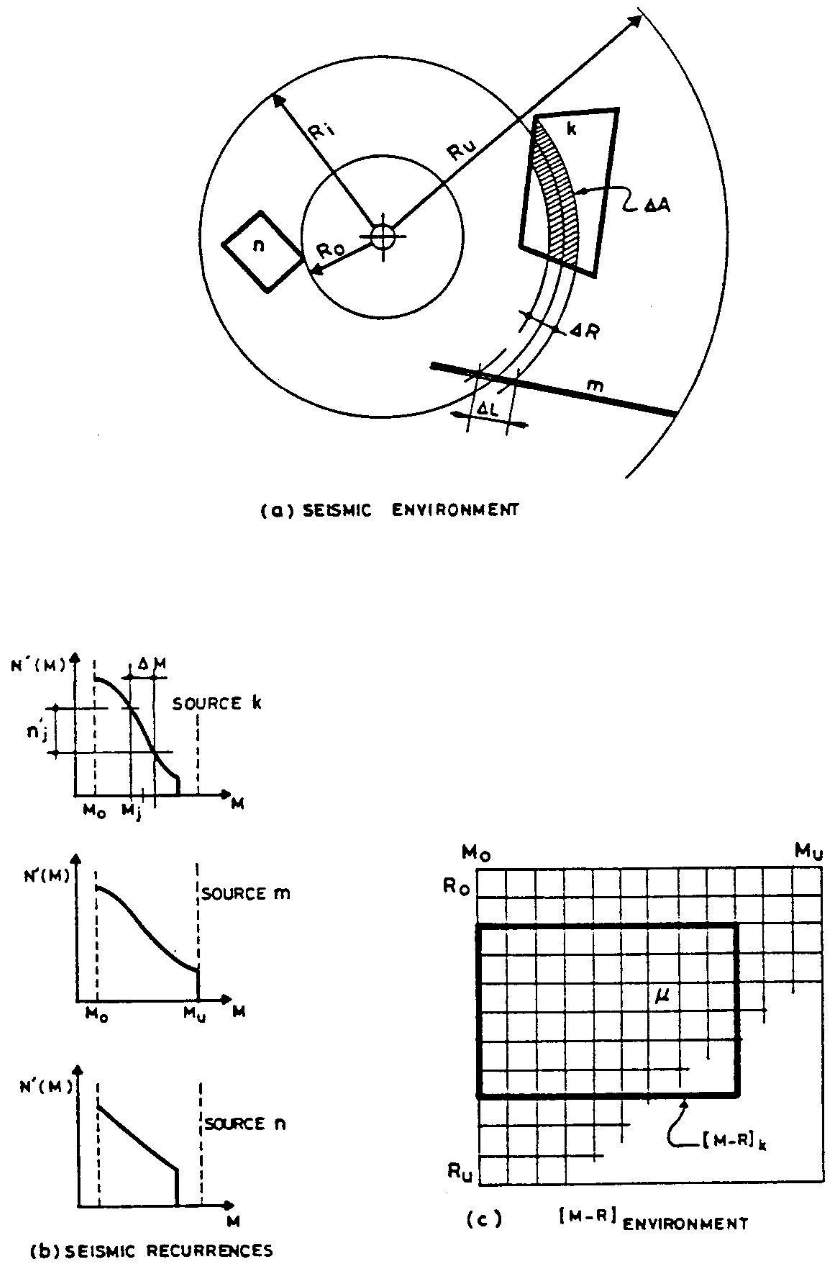
From the definition of $N_k(m)$ given by Eq. (1), Eq. (3) gives the number of occurrences in the interval ΔM around M_j .

The number of occurrences per year, at a distance R; contributed by the portion of the source k that is located at the distance R_{ij} is denoted by λ_{ijk} events per year and is estimated as:

$$\mathbf{\lambda_{ijk} = n_{jk} \quad \Delta A_{ik}} \ \textbf{for area sources, and}$$

$$\mathbf{\lambda_{ijk} = n_{jk} \quad \Delta L_{ik}} \ \textbf{for line sources} \qquad \mathbf{(4)}$$

This value due to source k, is entered at the location, i,j of the [M-R] matrix shown in the attached figure and the procedure is repeated for all i's and j's of the $[M-R]_k$ matrix.



Schematical Illustration of the Numerical Procedure
for Seismic Hazard Evaluation at Sites

The above procedure is repeated for all the sources in the environment. The contribution of all the sources to the seismicity of the site is obtained by superposition. The rate of occurrence of seismic events of magnitude M_j at a distance R; is given by,

$$\mu_{ij} = \Sigma \lambda_{ijk} \quad \textbf{(5)}$$

Where S is the total number of sources,

Up to this point the result is the [M-R] matrix for the seismic environment of the site under consideration. The attenuation relationship is used to obtain the rate of occurrence of various levels of ground motion severity at the site of interest. Denoting the attenuation relationship by "a" and expressing it as function of R and M,

$$\mathbf{a = f\,(R, M)} \quad \textbf{(6)}$$

The procedure for constructing the hazard curve at the site involves the following steps:

1) The maximum and minimum severities at the site are:

$\mathbf{a_{max}}$ = $\mathbf{f(R_o, M_u)}$, **top-right entry of [M-R] matrix, and**

$\mathbf{a_{min}}$ = $\mathbf{f(R_u, Mo)}$, **bottom-left entry of [M-R] matrix.**

The range of possible values of "a" is thus defined. The domain may be discretized into a convenient number of intervals a_{min}, a_1, a_2, a_{max}

2) Taking a severity level, a_k, the matrix [M-R] is scanned to identify all pairs of R_i, M_j, for which,

$$\mathbf{a_{ij} = f(R_i, M_j) > a_k}$$

The summation of all μ_{ij} for which $a_{ij} > a_k$ yields the average number of yearly occurrences, V_k of events whose severity exceeds the level a_k, Thus,

$$\mathbf{V_k = \Sigma_{all}\, \mu_{ij} \text{ such that } a_{ij} > a_k} \quad \textbf{(7)}$$

3) Repeating the procedure for all levels of severity in the state-space of "a" a graph of the site's seismic hazard (a loading condition recurrence graph) is obtained. A typical hazard graph which is a plot of the probability of PGA larger than "a" versus "a" in gravity units is illustrated in Figure below.

From the knowledge of the rate of occurrence of ground-motion severity at a site, Poisson model is then employed to model the recurrence of seismic loading as a stochastic process. The process will yield the so-called "acceleration zone graph" which is a plot of the return period with the load severity, a, in gravity units. The return period is defined as the time span in which the expected number of events is 1.0.

ISO-ACCELERATION MAPS

The above procedure is implemented by the Stanford Seismic Hazard Analysis (STASHA) expert system which is employed to construct hazard curves at specific sites and the iso-acceleration map for the Kingdom.

The grid option of STASHA is utilized to compute the peak ground acceleration (PGA) at intersection (node) of a longitudinal line with the latitudinal line at one degree intervals in both directions.

PGA values for 10% probability of being exceeded can be calculated for various exposure times belonging to the economical life of structures. The PGA's for a 50-year exposure time are plotted in the form of an iso-acceleration map.

MODELING OF SEISMIC ZONES

1. Correlation between seismic and tectonic data

(a) Earthquakes do not occur everywhere, but only in definite tectonically active areas and in strong accordance with movement and deformation of geological structures. Globally, there were close relation between active faults and strong earthquakes, but the relations are not so strong in other areas characterized by less long term seismicity. The Earth is partitioned among large seismogenic and aseismogenic belts, which are apportioned further into smaller source zones. The seismogenic source zones have active faults at different depths, concealed in the depth or exposed on the surface. A seismogenic zone is therefore a main unit that determines the seismic conditions of a territory. The source zones are of different size and kind. In every zone occur earthquakes up to a definite value of the seismic parameters. These are due to varying size, degree of competency, and rate of movement, so that earthquakes correspondingly vary with the parameters.

(b) Major earthquakes occur along tectonically active source zones having large faults. The zones which divide geological units having different history of development and large difference in rates of movement are the most seismically active. The larger is the disturbed structure and the greater is its competency, the larger is the fault plane affected by the abrupt movements and the sronger will be the earthquake. Correspondingly, every group of homogeneously disturbed structure with definite competency and size has a definite ceiling of magnitude value. The more is the rate of structure movements along a fault and the less is the competency of these structures, the more rapidly the stress needed for an abrupt displacement of a structure along a fault is accumulated and the more often arise earthquakes of the maximum magnitude value for this structure. Every tectonically active source zone has its own rate of movement along it and corresponding frequency of earthquake occurrences.

(c) Geological structures move abruptly on faults along tectonically homogeneous active zone not simultaneously but alternatively in different places of the zones. Alternatively, in different places in this zone arise earthquake of maximum magnitude for this zone. When a source of an earthquake of certain maximum strength was recorded in this homogeneous active zone, then earthquake of the same strength can occur anywhere along this zone. In other word, the probability of such an earthquake can be extrapolated and interpolated along homogeneous tectonically active zones.

2. Correlation between Earthquake Frequency and Mechanics of Faulting

The geological interpretation of the mechanism of an earthquake could possibly have started by Lawson in 1908, which was translated by Reid (1910) into quantitative terms. The concept established the theoretical and physical correlation between occurrence of earthquakes and deformation of tectonic structures.

The most important parameter in mechanics of faulting as related to occurrence of a seismic event is the seismic moment (Mo).

$$\mathbf{Mo = uAD = uLWD} \qquad \mathbf{(1)}$$

where u is the rigidity, A is the fault plane area, L and W are the length and width of the fault respectively, and D is the displacement. The amplitude of the long period waves is proportional to the seismic moment. Since the surface magnitude (Ms) is calculated by measuring the amplitude of the long period wave, there exist a close relationship between Mo and Ms, and so with Mo, length and displacement arising from static similarity. For this study, the relationships are obtained empirically, which is a world-wide data collection of corresponding magnitude, moment, length, width and displacement. The empirical relationships that were obtained are as follows:

$$\mathbf{Log\ Mo = [(1.62{+-}0.112)Ms + 15.1] {+-}0.3} \qquad \mathbf{(2)}$$

$$\mathbf{Log\ Mo = [(2.54{+-}0.087)Log\ L + 22.56] {+-}0.31} \qquad \mathbf{(3)}$$

$$\mathbf{Log\ Mo = [(2.61{+-}0.28)Log\ D + 26.32] {+-}0.44} \qquad \mathbf{(4)}$$

From (2-4), the following equations can be obtained when the standard deviation and standard error of estimate are not incorporated

$$\text{Log } L = 0.64Ms - 2.94 \qquad (5)$$

$$\text{Log } D = 0.62Ms - 4.3 \qquad (6)$$

Equation (2) is within the range of values (1.5-1.7) as obtained by Kanamori (1977), Hanks & Kanamori (1977). Equations (5) and (6) are close to Matsuda (1975) results which are 0.6, 2.9: and 0.6, 4 for the coefficients and constants respectively. The rupture is assumed to take place in the entire length of the homogeneous part of the fault or portion for segmented fault. The constraining equations for the fault length, dislocation, and magnitude are from (2-4)

$$1.52\text{Log}D + 7.25 < Ms < 1.69\text{Log}D + 6.65 \qquad (7)$$

$$1.55\text{Log}L + 4.36 < Ms < 1.6\text{Log}L + 4.94 \qquad (8)$$

The magnitude frequency relation of earthquakes satisfies the empirical relation (Gutenberg & Richter 1954)

$$\text{Log } N = a - bMs \qquad (9)$$

where N is the number of magnitude Ms or greater, a and b the seismicity parameters. Equation (9) holds down to the level of micro-events (Mogi,1962) which indicates a fundamental physical understanding of the fracture process can be known if the relation can be explained completely. The Mo and Ms are both measures of the strength of an earthquake, so that (9) can be expressed in terms of Mo by means of (2). The theoretical consideration that the magnitude scale saturates at higher values of magnitude, but not with Mo is appropriate to substitute the seismic moment frequency relation for characterizing earthquake occurrences. From (2) and (9), a power law size distribution of earthquakes can be obtained (Wyss 1973)

$$N(Mo) = Amo^{(-B)} \qquad (10)$$

$$A = \exp[(a + bc/d)\ln 10]$$

$$B = b/d$$

where a and b, c and d are the constant and coefficient in (9) and (2) respectively. From Wyss (1973), the total moment of a given earthquake population is the integral

$Mo(tot) = (AB/(1-B)[Mo^{(1-B)}]$ (11)

where the upper and lower limits of integration are Mo(max) and Mo(min) as the maximum and minimum seismic moment in a given earthquake population respectively. In (10) it is assumed that the Mo(max) is attained when N(Mo)=1, so that $A=Mo^{B}$. Likewise, in (9) the Mmax is also attained when N(M) =1. If Mo(min) is insignificant compared to Mo(max), (11) becomes approximately equal to

$Mo(tot)= B/(1-B)Mo(max)$ (12)

From Wesnousky and Scholz (1983), the repeat time (Tmax) of (11) is

$T(max) = Mo(tot)/Mo(g)$ (13)

where Mo(g) is the geologically assessed rate of moment release on a fault.

In (6), the recurrence time (Tmax) of an event with dislocation D is

$T(max) = D/S$ (14)

where S is the linear average seismic slip rate.

The geologically assessed rate of moment release is not available in eastern Saudi Arabia. To be able to utilize the concepts enunciated in (9-14) for the correlation of regional seismicity to tectonics, there was a need to treat the 3 set of seismic data (historical, instrumental, recent) into one group in each seismogenic source zone in terms of Ms, to obtain the required parameters. The conversion equation was (Al-Amri et al 1998).

$Ms = 1.14\ Mb - 0.9$ (15)

where Mb is the body-wave magnitude.

Wesnousky and Scholz (1983) had indicated that the average geological moment release rate is almost the same as the average seismic moment release rate in 200-300 year of seismic data, and similar to the geological rate for 400 year of data. It is assumed then that the findings for seismic moment release rate have also the same similarities to the linear average seismic slip and or spreading rate. The period of observation in each source zone is counted from the earliest recorded year of the data up to 2003.

The geologically assessed rate of moment release is assumed to be equal to the ratio of the cumulative seismic moment release and period of observation. This assumption was also applied to obtain the linear average seismic slip or spreading rate. The average slip rate in each zone with sufficient seismic data could be compared to other findings obtained from different sources for validation. If the seismic slip rates are compatible to other results, presumably the seismic moment release rates would also qualify. When sufficient data are not available, the other alternatives could be to assume the applicability of the other parameters obtained in neighboring seismic source zones and or using (12).

The expected maximum magnitude in each seismogenic source zone is either taken from (9) [Mmax(S)], or the observed maximum magnitude Mmax(O) from the set of seismic data in each source zone, and or the estimated magnitude [Mmax(L)] from fault length of the existing fractures in each respective seismogenic source zone. The expected Mmax(S) and or Mmax(O) are then correlated to fault length in (5) or dislocation in (6), and the magnitude from crustal depth (H) which is given as

$$\mathbf{Mmax(H) = 4Log\ H + 1.8} \qquad \mathbf{(16)}$$

The corresponding feasibilities in (5), (6), (9) and (16) could indicate possible association and characterization of the most likely source of the given earthquake population in each seismogenic source zone.

Earthquakes are not equally distributed in space-time, although probably the seismic events follow physical causalities which are not fully known. Therefore, at least the strongest earthquakes can be assumed to be independent random events. Considering the probability of occurrence of these seismic events in a time interval (t), and assuming the Poisson process as the appropriate probability function applicable in the source zones, then the probability of occurrence (Pr) of an event with return time (Tmax) is given as

$$\mathbf{Pr = 1\text{-}exp(-t/Tmax)} \qquad \mathbf{(17)}$$

Because there were different constraints encountered in the correlation processes such as scarcity of seismic data and inadequate information concerning fault parameters. It became necessary to refer to (17) as an additional data and basis in the decision processes. The time interval is assumed to be 100 years.

Slemmons (1981) had described a characterization scheme for fault rate activity. The classification is as follows: (a) fault not active; (b) hardly active; (c) well developed geomorphologically (medium to high); (d) high; (e) very high; and (f) extremely high. The basis of the classification was the inverse of the linear slip rate as the constant slope of a linear relation between recurrence time and dislocation (eq.14) which is expressed in terms of magnitude. For slip rate of 10 cm/yr, the fault rate of activity is extremely high for magnitude range 4.8-9, for slip rate of 1 cm/yr, the fault rate activity varies from extremely high to very high for the magnitude range 4.7-9, for slip rate 0.1 cm/yr, the fault rate activity also varies from extremely high-to very high- to high for the magnitude range 4.7-9, for slip rate 0.01 cm/yr, the fault rate activity varies from very high- to high- to medium high for the magnitude range 4.7-9, and for slip rate 0.001 cm /yr, the fault rate activity varies from high-to medium high-to hardly active - to fault not active for the magnitude range 4.7-9.

DELINEATION OF SEISMIC ZONES

In the identification and delineation of seismic source zones, some criteria were followed and utilized as guidelines. The criteria are:

1. Seismological parameters- map of the planar distribution of earthquake epicenters that could indicates both seismogenic provinces and seismoactive faults, and occurrence. Of large earthquakes, the level of which depends upon on the seismic activity in the region. When required and necessary, the magnitudes can be converted to energy values to show the energy flux distribution for better correlation. This procedure can also be applied to the parameter intensity by means of an appropriate conversion relation or conversely a distribution map of the observed maximum intensities in the region. Historical earthquakes are described mostly in terms of intensity and it would seem appropriate to use this parameter as an additional guide. In using the spatial distribution of epicenters as a guideline, boundaries of zones are drawn in such a way that a cluster or more clusters of earthquakes are included and crossed the region of minimum density of epicenters, but do not intersect the main tectonic provinces. The scatter of few seismic data over a wider area could lead to the formation of a seismic source zone with one event, provided the magnitude level is high compared to the level of background seismicity in the region. In principle, this system of clustering can also be applied to energy or intensity distribution to draw the boundary lines that encloses a particular seismic zone same as with the denseness of the epicenters of earthquake events.

2. Geological parameters- map of regional tectonics in the area which indicates the location of joints, faults, lineaments and rift systems that are associated with seismic activities. Fracture dislocations are the sources of seismic events. Seismogenic source zones are selected that are composed of a system of faults or lineaments or rift zones whose boundaries do not traverse generally other tectonic units.

3. Geophysical parameters- maps of heat flow and gravity anomaly distributions are useful in the interpretation on the nature of geologic structures. As can be seen on the two maps, there were gradual and distinct changes on the contours shapes and values. The contours shapes and spacing seemed to be consistent with the tectonic locations and orientations in the region. Seismic source zones boundaries are therefore drawn on these distinct or gradual changes.

The boundaries were the results in the inter-agreement of the 3 criteria, with the higher priority given to the spatial distribution of the earthquake epicenters due to statistical needs in seismicity investigation. Likewise, it is observed that some earthquakes cannot be connected to some line sources.

From these considerations, there were twenty five (25) identified and delineated seismogenic source zones for Saudi Arabia .

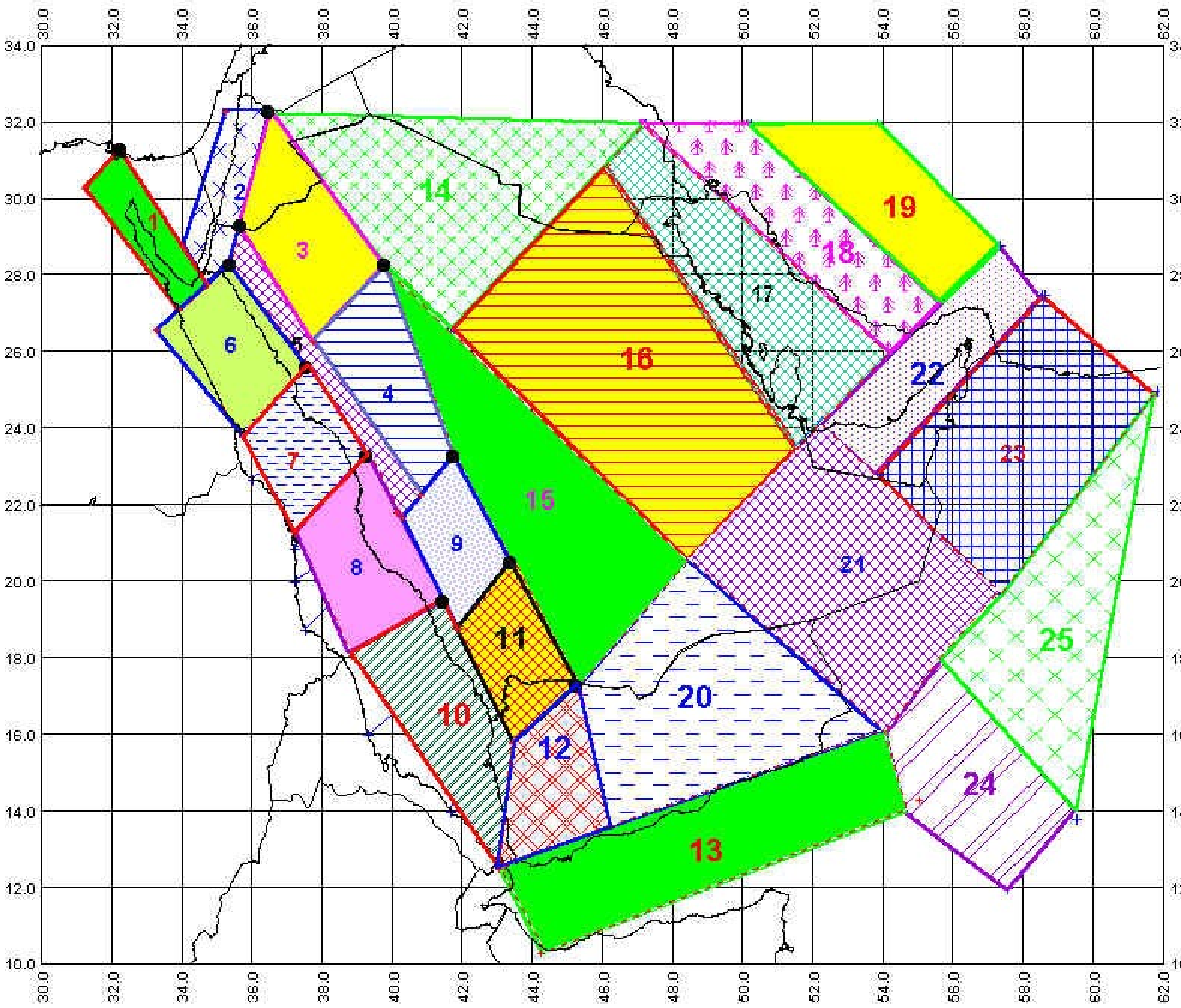


Figure 6. Seismic Source Zones of the Arabian Peninsula and Adjoining Regions

SEISMIC SOURCE ZONES

The characterization of the seismogenic source zones is composed of two parts. These are the brief discussions covering the possible association of each source zone to the tectonic and seismicity model of the areas contained in each source zone. The other part is a logic tree diagram for graphical description of the physical and seismicity parameters involved in seismotectonic correlation.

Two methods of approach were employed in the study. These are seismicity and fractures. Under the seismicity approach, the set of seismic data in each source zone was utilized to plot the magnitude-frequency relation, and for the estimation of the linear seismic slip and seismic moment release rates. From the frequency graphs, the respective seismicity parameters were determined for correlation to tectonic structures and probable earthquake source mechanisms. Under the second approach, the tectonic structures contained in each source zones were examined based on existing geological/tectonic maps for identification and association to the types of earthquake source mechanisms, and to the seismicity of the source area. Combination of the two approaches lead to the preliminary framework of a seismotectonic model for each seismogenic source zone.

From the findings, there were at most two types of sources for the tectonic model. These are the fault and area source. Under the fault source are the transcurrent and normal faults and their respective variations. Under the area source are the seismic events not directly associated to known presence of fractures or are off located, and or the sudden or randomly distributed dislocations of the ground within the source zones. Presumably, the causes of these seismic events under the area source are due to lateral and vertical structural discontinuities, or connected to some anomalous behavior of geophysical phenomena, and or undetected fractures.

For earthquake source mechanisms, there are also at most two types. These are the extrusion and transcursion mechanisms. The zones of extrusion are the seats of volcanic activity and high heat flow. Seismological and other geophysical data suggest that ridges and their continental extension are characterized by rifting, spreading, and other aspects of extensional tectonics.

SEISMIC ZONATION

Seismic zonation is the division of geographic region into smaller areas or zones expected to experience the same relative severity of an earthquake hazard (e.g., ground shaking, ground failure, surface faulting, tsunami wave runup, etc.,). The resulting zonation maps provide community policymakers and development.

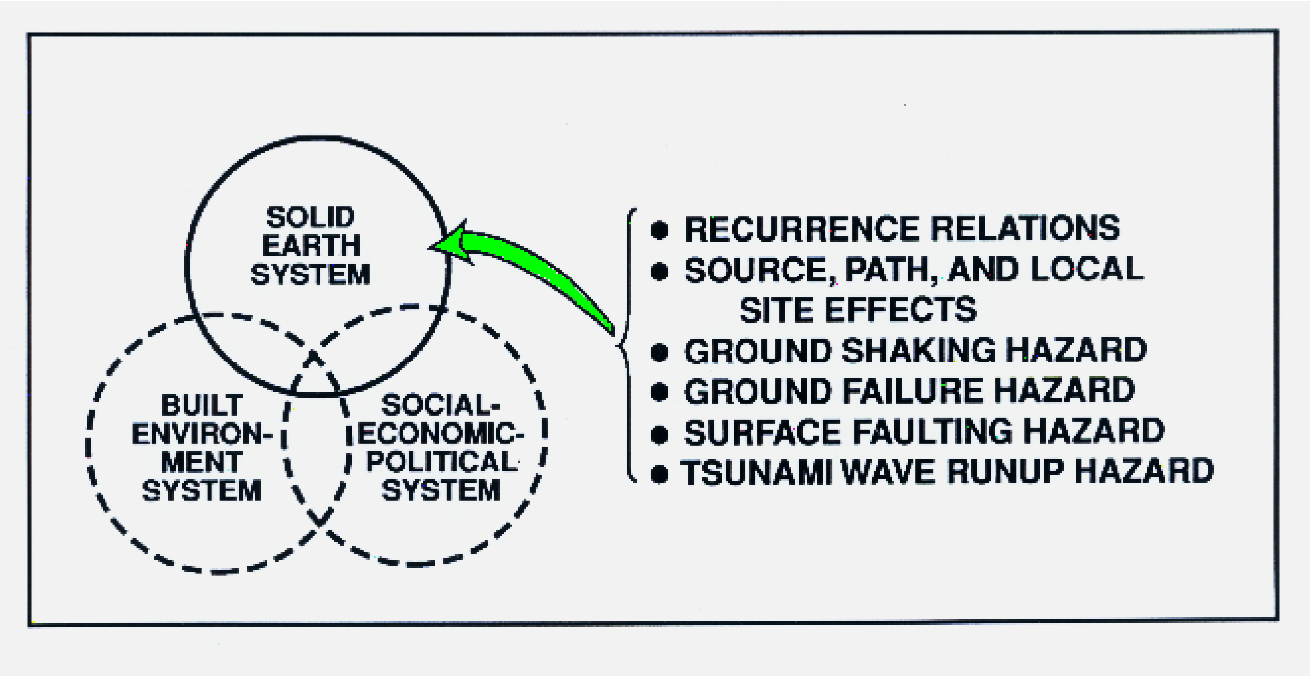
The key questions are summarized below:

1. **Solid Earth System** (i.e., defines the physical characteristics of the source, path, and site which control earthquake hazards (e.g., ground shaking and ground failure hazards)).
   - ❖ Where have earthquakes occurred in the past?
   - ❖ Where are they occurring now?
   - ❖ What is the magnitude and depth distribution of the past and present seismicity?
   - ❖ How often have earthquakes of a given magnitude recurred?
   - ❖ What are the dominant earthquake generating mechanisms?
   - ❖ What levels of ground shaking have occurred in the past? Ground failure? Surface fault rupture? Tsunami wave runup?
   - ❖ What are the maximum levels that might be expected in future earthquakes?

2. **Built Environment System**, (I,e., defines the temporal and spatial distribution of buildings and lifeline systems exposed to earthquake hazards).
   - ❖ What are the physical characteristics of the present inventory of buildings and lifeline systems (e.g., age, type of materials, number of stories, elevation, plan, foundations, etc.)? The future inventory?
   - ❖ How have these buildings and lifeline systems performed in past earthquakes (e.g., what are the vulnerability relations for each type of building and lifeline?

3. **Social-Economic-Political System**, (I,e., defines the community's earthquake risk management policies and practices (e.g., mitigation, preparedness, emergency response, and recovery).
   - ❖ What risk management policies and practices (i.e., building and land use regulations) have been adopted by the community in the past?

- How have they been enforced?
- How effective have they been?



REDUCTION OF COMMUNITY VULNERABILITY

BUILT ENVIRONMENT

- Location value, exposure, and vulnerability of buildings and lifelines at risk earthquake physical effects (hazards) which can cause damage, failure, lc function, release of hazardous materials, injuries, and deaths.

HAZARD ENVIRONMENT	POLICY ENVIRONMENT
* Physical effects such as: Ground shaking; liquefaction; landslides; surface fault rupture; tectonic deformation; fires, and flood waves from seiche, tsunami, and dam break generated in an earthquke and the aftershock sequence; each potentially impacting the built environment.	*Social, technical, Aadministrative, political, legal, and economic forces which shape a community's policies and practices for: earthquake risk management (i.e., prevention, itigation, preparedness, prediction and warning, intervention, emergency), public awareness, training, education, and insurance.

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