Engineering Seismology

Abdullah M. Al-Amri

Dept. of Geology & Geophysics

King Saud University, Riyadh

alamri.geo@gmail.com

www.a-alamri.com

2018

GEOLOGICAL HAZARDS

INTRODUCTION

Most geologic events cannot be prevented or even predicted with any precision. Landslides are an exception: they can often be prevented. Areas prone to such events can be identified as earthquake fault zones, active volcanoes, and coastal areas susceptible to tsunamis. However, not all earthquake faults have been identified. Estimates of an occurrence of a given hazardous event are probabilistic, based on consideration of the magnitude of an event and its occurrence in time and space. Other measures-duration, areal extent, speed of onset, geographic dispersion, frequency-can be anticipated with even less precision.

Geologic events are distinctive for their extremely rapid onset. Unlike a flood or hurricane, whose impact at a site can be forecast hours or days in advance, earthquakes give virtually no warning. Volcanoes often show signs of a general increase in activity but give little or no warning of the actual eruption. Tsunamis travel great distances over the open ocean; one triggered off the cost of Peru might hit the coast of Japan 18 hours later, giving reasonable warning time, but the same tsunami would hit the coast of Peru with almost no warning at all.

In addition to speed of onset, geologic hazards also tend to have impacts covering large areas. Earthquakes can cause damage over millions of square kilometers, and tsunamis travel the entire ocean and cause major damage thousands of kilometers from their point of origin. For these reasons, non-structural mitigation measures, such as land-use zoning or the development of monitoring systems, tend to be particularly effective.

MAJOR GEOLOGICAL HAZARDS CAUSED BY EARTHQUAKES

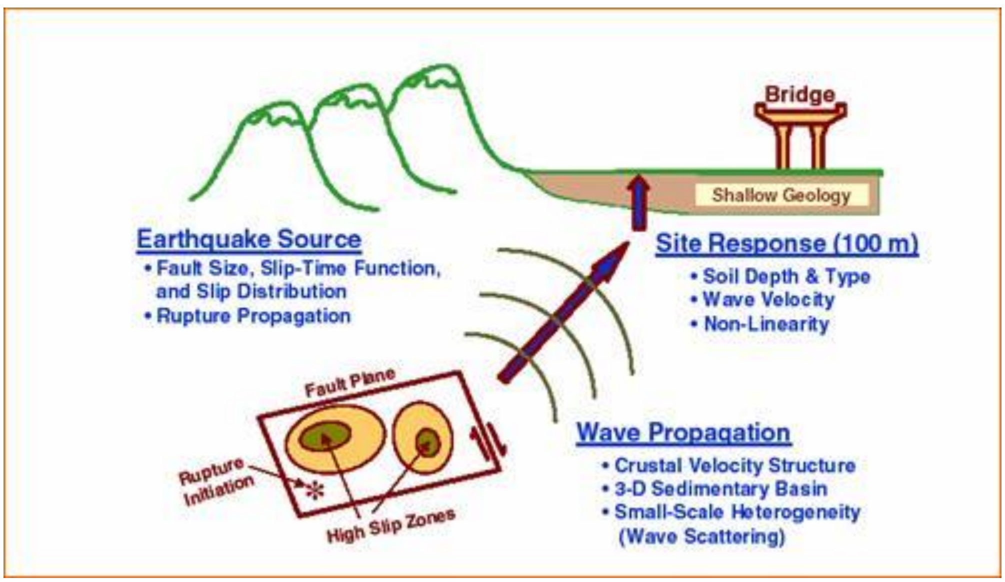
1. **Ground Shaking**
2. **Surface Faulting**
3. **Tsunamis**
4. **Landslides and Liquefaction**
    - **Rock Avalanches**
    - **Rapid Soil Flows**
    - **Rock Falls**
    - **Mud Flows**
    - **Flow Failure**
    - **Loss of Bearing Strength**
    - **Lateral Spreads**

(A) Primary Causes of Earthquake Damage

Ground Motion

Most damage during an earthquake is caused by **ground motion**. A commonly measured ground motion is peak ground acceleration (**PGA**), which is expressed as a percentage of the acceleration of gravity (**g**). The larger an earthquake's magnitude, the stronger the ground motion it generates. The level of ground motion at a site depends on its distance from the epicenter -- the closer a site is to the epicenter, the stronger the ground motion, and vice versa. Strong ground motion could also induce secondary hazards such as ground-motion amplification , liquefaction , and landslide under certain site conditions.

The local geology and soil also play very important roles in earthquake damage. Soft soils overlying hard bedrock tend to amplify the ground motions -- this is known as **ground-motion amplification.** Amplified ground motion can cause excess damage, even to sites very far from the epicenter.



Ground Shaking

Most earthquake damage is caused by ground shaking. The magnitude of an earthquake, distance to the earthquake focus, type of faulting, depth, and type of material are important factors in determining the amount of ground shaking that might be produced at a particular site.

Ground shaking is a term used to describe the vibration of the ground during an earthquake. Ground shaking is caused by body waves and surface waves. As a generalization, the severity of ground shaking increases as magnitude increases and decreases as distance from the causative fault increases. Although the physics of seismic waves is complex, ground shaking can be explained in terms of body waves, compressional, or P, and shear, or S, and surface waves, Rayleigh and Love.

P waves propagate through the Earth with a speed of about 15,000 miles per hour and are the first waves to cause vibration of a building. S waves arrive next and cause a structure to vibrate from side to side. They are the most damaging waves, because buildings are more easily damaged from horizontal motion than from vertical motion. The P and S waves mainly cause high-frequency vibrations; whereas, Rayleigh waves and Love waves, which arrive last, mainly cause low-frequency vibrations. Body and surface waves cause the ground, and consequently a building, to vibrate in a complex manner. The objective of earthquake-resistant design is to construct a building so that it can withstand the ground shaking caused by body and surface waves.

In land-use zoning and earthquake-resistant design, knowledge of the amplitude, frequency composition, and the time duration of ground shaking is needed. These quantities can be determined from empirical (observed) data correlating them with the magnitude and the distribution of Modified

Mercalli intensity of the earthquake, distance of the building from the causative fault, and the physical properties of the soil and rock underlying the building. The subjective numerical value of the Modified Mercalli Intensity Scale indicates the effects of ground shaking on man, buildings, and the surface of the Earth.
When a fault ruptures, seismic waves are propagated in all directions, causing the ground to vibrate at frequencies ranging from about 0.1 to 30 Hertz. Buildings vibrate as a consequence of the ground shaking; damage takes place if the building cannot withstand these vibrations.

Compressional waves and shear waves mainly cause high-frequency (greater than 1 Hertz) vibrations which are more efficient than low-frequency waves in causing low buildings to vibrate. Rayleigh and Love waves mainly cause low-frequency vibrations which are more efficient than high-frequency waves in causing tall buildings to vibrate.

Because amplitudes of low-frequency vibrations decay less rapidly than high-frequency vibrations as distance from the fault increases, tall buildings located at relatively great distances (60 miles) from a fault are sometimes damaged.
Four principal characteristics which influence the damage that can be caused by an earthquake's ground shaking-size, attenuation, duration, and site response. These factors are also related to the distance of a site from the earthquake's epicenter .

(1) Earthquake Severity or Size: The severity of an earthquake can be measured two ways: its intensity and its magnitude. Intensity is the apparent effect of the earthquake at a specific location. The magnitude is related to the amount of energy released.

Intensity is measured on various scales. The one most commonly used in the Western Hemisphere is the twelve-level Modified Mercalli Index (MMI), on which the intensity is subjectively evaluated by describing the extent of damage. Figure 11 -2 shows the approximate relationships of magnitude, intensity at the epicenter, and other seismic parameters, comparing energy release with equivalent tons of TNT.

The Richter Scale, which measures magnitude, is the one most often used by the media to convey to the public the size of an earthquake. Magnitude is easier to determine than intensity, since it is registered on seismic instruments, but it does present some difficulties. While an earthquake can have only one magnitude, it can have many intensities which affect different communities in different ways. Thus, two earthquakes with an identical Richter magnitude may have widely different maximum intensities at different locations.

(2) Attenuation: Attenuation is the decrease in the strength of a seismic wave as it travels farther from its source. It is influenced by the type of materials and structures the wave passes through (the transmitting medium) and the magnitude of the earthquake.

(3) Duration: Duration refers to the length of time in which ground motion at a site exhibits certain characteristics such as violent shaking, or in which it exceeds a specified level of acceleration measured in percent of gravity (g). Larger earthquakes are of greater duration than smaller ones. This characteristic, as well as stronger shaking, accounts for the greater damage caused by larger earthquakes.

(4) Site Response: The site response is the reaction of a specific point on the earth to ground shaking. This also includes the potential for ground failure, which is influenced by the physical properties of the soil and rock underlying a structure and by the structure itself. The depth of the soil layer, its moisture content, and the nature of the underlying geologic formation-unconsolidated material or hard rock-are all relevant factors. Furthermore, if the period of the incoming seismic wave is in resonance with the natural period of structures and/or the subsoil on which they rest, the effect of ground motion may be amplified.

In the 1985 Mexico City earthquake, the period of the seismic wave was close to the natural period of the Mexico City basin, considering the combination of soil type, depth, and shape of the old lake bed. The wave reached bedrock under the city with an acceleration level of about 0.04g. By the time it passed through the clay subsoil and reached the surface, the acceleration level had increased to 0.2g, and the natural vibration period of the buildings with 10 to 20 floors increased the force to 1.2g, 30 times the acceleration in the bedrock. Most buildings would have resisted 0.04g acceleration, and the earthquake-resistant buildings destroyed would have resisted 0.2g, but the waves that were amplified to 1.2g caused all buildings they reached to collapse (Anderson, 1985).

Surface Faulting

Surface faulting -- the differential movement of the two sides of a fracture at the Earth's surface-- is of three general types: strike-slip, normal, and reverse (or thrust). Combinations of the strike-slip type and the other two types of faulting can be found. Although displacements of these kinds can result from landslides and other shallow processes, surface faulting, as the term is used here, applies to differential movements caused by deep-seated forces in the Earth, the slow movement of sedimentary deposits toward the Gulf of Mexico, and faulting associated with salt domes. Death and injuries from surface faulting are very unlikely, but casualties can occur indirectly through fault damage to structures.

Surface faulting, in the case of a strike-slip fault, generally affects a long narrow zone whose total area is small compared with the total area affected by ground shaking. Nevertheless, the damage to structures located in the fault zone can be very high, especially where the land use is intensive. A variety of structures have been damaged by surface faulting, including houses, apartments, commercial buildings, nursing homes, railroads, highways, tunnels, bridges, canals, storm drains, water wells, and water, gas, and sewer lines. Damage to these types of structures has ranged from minor to very severe.

The displacements, lengths, and widths of surface fault ruptures show a wide range. Fault displacements in the United States have ranged from a fraction of an inch to more than 20 feet of differential movement. As expected, the severity of potential damage increases as the size of the displacement increases. The lengths of the surface fault ruptures on land have ranged from less than 1 mile to more than 200 miles. Most fault displacement is confined to a narrow zone ranging from 6 to 1,000 feet in width, but separate subsidiary fault ruptures may occur 2 to 3 miles from the main fault. The area subject to disruption by surface faulting varies with the length and width of the rupture zone.

Liquefaction Induced

Liquefaction is not a type of ground failure; it is a physical process that takes place during some earthquakes that may lead to ground failure. As a consequence of liquefaction, clay-free soil deposits, primarily sands and silts, temporarily lose strength and behave as viscous fluids rather than as solids.

Liquefaction takes place when seismic shear waves pass through a saturated granular soil layer, distort its granular structure, and cause some of the void spaces to collapse. Disruptions to the soil generated by these collapses cause transfer of the ground-shaking load from grain-to-grain contacts in the soil layer to the pore water. This transfer of load increases pressure in the pore water, either causing drainage to occur or, if drainage is restricted, a sudden buildup of pore-water pressure. When the pore-water pressure rises to about the pressure caused by the weight of the column of soil, the granular soil layer behaves like a fluid rather than like a solid for a short period. In this condition, deformations can occur easily.

Liquefaction is restricted to certain geologic and hydrologic environments, mainly areas where sands and silts were deposited in the last 10,000 years and where ground water is within 30 feet of the surface.

Generally, the younger and looser the sediment and the higher the water table, the more susceptible a soil is to liquefaction.
Liquefaction causes three types of ground failure: **lateral spreads**, **flow failures**, and **loss of bearing strength**. In addition, liquefaction enhances ground settlement and sometimes generates sand boils (fountains of water and sediment emanating from the pressurized liquefied zone). Sand boils can cause local flooding and the deposition or accumulation of silt.

Lateral Spreads

Lateral spreads involve the lateral movement of large blocks of soil as a result of liquefaction in a subsurface layer. Movement takes place in response to the ground shaking generated by an earthquake. Lateral spreads generally develop on gentle slopes, most commonly on those between 0.3 and 3 degrees. Horizontal movements on lateral spreads commonly are as much as 10 to 15 feet, but, where slopes are particularly favorable and the duration of ground shaking is long, lateral movement may be as much as 100 to 150 feet. Lateral spreads usually break up internally, forming numerous fissures and scarps. Damage caused by lateral spreads is seldom catastrophic, but it is usually disruptive. Lateral spreads are destructive particularly to pipelines.

Flow Failures

Flow failures, consisting of liquefied soil or blocks of intact material riding on a layer of liquefied soil, are the most catastrophic type of ground failure caused by liquefaction. These failures commonly move several tens of feet and, if geometric conditions permit, several tens of miles. Flows travel at velocities as great as many tens of miles per hour. Flow failures usually form in loose saturated sands or silts on slopes greater than 3 degrees. Flow failures can originate either underwater or on land. Many of the largest and most damaging flow failures have taken place underwater in coastal areas.

Loss of Bearing Strength

When the soil supporting a building or some other structure liquefies and loses strength, large deformations can occur within the soil, allowing the structure to settle and tip.

Earthquake-Induced Landslides

Earthquake-induced landslides occur under a broad range of conditions: in steeply sloping to nearly flat land; in bedrock, unconsolidated sediments, fill, and mine dumps; under dry and very wet conditions. The principal criteria for classifying landslides are types of movement and types of material. The types of landslide movement that can occur are falls, slides, spreads, flows, and combinations of these. Materials are classified as bedrock and engineering soils, with the latter subdivided into debris (mixed particle size) and earth (fine particle size) (Campbell, 1984).

Moisture content can also be considered a criterion for classification: some earthquake-induced landslides can occur only under very wet conditions. Some types of flow failures, grouped as liquefaction phenomena, occur in unconsolidated materials with virtually no clay content. Other slide and flow failures are caused by slipping on a wet layer or by interstitial clay serving as a lubricant. In addition to earthquake shaking, trigger mechanisms can include volcanic eruptions, heavy rainstorms, rapid snowmelt, rising groundwater, undercutting due to erosion or excavation, human-induced vibrations in the earth, overloading due to construction, and certain chemical phenomena in unconsolidated sediments.

The frequency of occurrence of earthquake-induced landslides is related primarily to the magnitude of the earthquake and aftershock but also to local geologic conditions. The frequency scale used here is based on a survey of landslides associated with 40 historic earthquakes.

(1) Rock Avalanches: Rock avalanches originate on over-steepened slopes in weak rocks. They are uncommon but can be catastrophic when they occur. The Huascarán, Peru, avalanche which originated as a rock and ice fall caused by the 1970 earthquake was responsible for the death of approximately 20,000 people.

(2) Rock Falls: Rock falls occur most commonly in closely jointed or weakly cemented materials on slopes steeper than 40 degrees. While individual rock falls cause relatively few deaths and limited damage, collectively, they rank as a major earthquake-induced hazard because they are so frequent.

Campbell, R.H., et al "Landslides Classification for Identification of Mud Flow and Other Landslide Hazards" and Keefer, P.K. "Landslides Caused by Earthquakes" in Proceedings of the Geologic and Hydrologic Training Program, Open File Report 84-760 (Reston, Virginia: U.S. Geological Survey, 1984).

(3) Mud Flows: Mud flows are rapidly moving wet earth flows that can be initiated by earthquake shaking or a heavy rainstorm. While the term is used in several ways, in this chapter "mud flow" is used to designate the phenomena associated with earthquake shaking. Underwater landslides, also classified as mud flows, may occur at the margins of large deltas where port facilities are commonly located. Much of the destruction caused by the 1964 Seward, Alaska, earthquake was caused by such a slide. The term "mudflow," in keeping with common practice, is used as a synonym for "lahar," a phenomenon associated with volcanoes.

Tsunamis

Tsunamis are water waves that are caused by sudden vertical movement of a large area of the sea floor during an undersea earthquake. Tsunamis are often called tidal waves, but this term is a misnomer. Unlike regular ocean tides, tsunamis are not caused by the tidal action of the Moon and Sun.

The height of a tsunami in the deep ocean is typically about 1 foot, but the distance between wave crests can be very long, more than 60 miles. The speed at which the tsunami travels decreases as water depth decreases. In the mid-Pacific, where the water depths reach 3 miles, tsunami speeds can be more than 430 miles per hour. As tsunamis reach shallow water around islands or on a continental shelf; the height of the waves increases many times, sometimes reaching as much as 80 feet. The great distance between wave crests prevents tsunamis from dissipating energy as a breaking surf; instead, tsunamis cause water levels to rise rapidly along coast lines.

Tsunamis and earthquake ground shaking differ in their destructive characteristics. Ground shaking causes destruction mainly in the vicinity of the causative fault, but tsunamis cause destruction both locally and at very distant locations from the area of tsunami generation.

(B) Secondary Causes of Earthquake Damage

While earthquakes may produce ground shaking, surface faulting, and vertical movements that cause direct damage to buildings and land, damage and personal injury may also be caused by several additional factors.

Earthquakes may trigger ground failures such as landslides, differential compaction of soil, and liquefaction of water-saturated deposits like landfills, sandy soils, and river deposits. Such ground failures may cause more damage to structures than the shaking itself. Earthquakes may also cause destructive water waves such as tsunamis and seiches. Non-structural building components like ceiling panels, windows, and furniture can cause severe injury if shaking causes them to shift or break. Broken or impaired lifelines (gas, water, or electric lines and transportation and communication networks) can produce hazardous situations and distress to a community. A reservoir can be a hazard, should shaking cause the dam to fail.

1. Ground Failure

Major property damage, death, and injury have resulted from ground failures triggered by earthquakes in many parts of the world. **Ground failures** grouped as liquefaction can be subdivided into several types. The two most important are rapid earth flows and earth lateral spreads.

(A) Rapid Earth Flows: Rapid earth flows are the most catastrophic type of liquefaction. Large soil masses can move from tens of meters to several kilometers. These flows usually occur in loose saturated sands or silts on slopes of only a few degrees; yet they can carry boulders weighing hundreds of tons.

(B) Earth Lateral Spreads: The movement of surface blocks due to the liquefaction of subsurface layers usually occurs on gentle slopes (up to 3 degrees). Movement is usually a few meters but can also be tens of meters. These ground failures disrupt foundations, break pipelines, and compress or buckle engineered structures. Damage can be serious with displacements on the order of one or two meters.

2. Structural Failure of Buildings

A building's structure may be damaged if its vibratory response to ground motion exceeds design limits. The response depends on the interaction between structural elements of the building and the direction, frequency, and duration of ground motion. These factors must be considered to produce a building design that prevents structural failure during earthquakes. In the absence of proper design, a building is exposed to greater risk of earthquake damage, particularly if the building has been subjected to prior strong earthquakes.

Importance of Type of Construction to Building Damage

Usually, buildings can better withstand the vertical component of the earthquake-induced ground motion because they are designed to resist the large vertical loads generated by their own weight. Many are, however, vulnerable to large horizontal motions. Resistance to horizontal motion is usually accomplished by using lateral bracing and strong connections to hold structural elements together. Horizontal elements like floors can then distribute the building's weight to the building's strong vertical elements (Yanev, 1974).

Construction that provides a continuous path to transfer the lateral load from roof to foundation is more resistant to ground shaking than construction in which that path can be easily broken. For example, a well-nailed wood frame house resists ground shaking better than an unreinforced brick house because, once the brick cracks, the path along which the lateral load is transferred is broken

Proper ties between the foundation and the structure and between the various elements of the structure are essential for good earthquake resistance. Buildings or other structures that are poorly attached or unattached to their foundations may shift off the foundation during an earthquake.

Importance of Frequency of Ground Shaking to Building Damage

Building damage commonly depends on the frequency of ground motion. Damage can be particularly severe if the frequency of ground motion matches the natural vibration frequencies of the structure. In this case, the shaking response of the structure is enhanced, and the phenomenon is called resonance. Tall buildings, bridges, and other large structures respond most to low-frequency ground shaking, and small structures respond most to high-frequency shaking

Tall buildings in sedimentary basins often suffer disproportionate damage because wave resonance in the basin amplifies low-frequency ground vibrations.

Importance of Building Shape to Damage

The shape of a building can influence the severity of damage during earthquakes. Buildings that are L or U shaped in plan view (as seen from the air) may sustain more damage than a symmetrical building. This damage occurs because large stresses develop at the intersection between the building's segments, which respond differently to ground vibrations of different frequencies and different directions of motion. A building with sections that differ in height or width may develop large stresses at certain points because each section will vibrate at its own natural frequency in response to ground shaking. Separate buildings that vibrate at different frequencies can damage each other if they are built close together.

Importance of Past Earthquakes to Building Damage

The history of a building and its exposure to prior earthquakes are also important in estimating the amount of damage it may sustain in future earthquakes. People often assume that a building that has survived an earthquake with no visible damage will likely not be damaged in subsequent earthquakes. However, ground shaking can weaken a building by damaging walls internally. Failure to detect and strengthen concealed damage can lead to complete destruction in a subsequent earthquake.

3. Hazards of Non-structural Building Components

Non-structural Hazards

The non-structural elements of a building include parapets, architectural decorations (such as terra cotta cornices and ornamentation), chimneys, partition walls, ceiling panels, windows, light fixtures, and building contents. Displacement or distortion of these elements during ground shaking can be a major hazard to building occupants and result in extensive building damage. Damage to the non-structural elements of a building can include the destruction of costly equipment, such as computer systems, and the loss or extensive disorganization of important company records.

Damaged Lifelines

Lifelines include the utilities (power, water, gas), communication networks, and transportation systems that crisscross and link our communities. Damage to these lifelines by earthquakes can create dangerous situations. Broken gas and power lines are serious threats to safety, largely because of risk of fire. Cracked water mains reduce the amount of water available for fire suppression. Lack of communication isolates people from help and needed information . Blocked or damaged transportation routes interfere with the ability of emergency personnel to respond promptly to requests for assistance.

LIQUEFACTION

Liquefaction is a phenomenon in which the strength and stiffness of a soil is reduced by earthquake shaking or other rapid loading. Liquefaction and related phenomena have been responsible for tremendous amounts of damage in historical earthquakes around the world. **Liquefaction** occurs in saturated soils, that is, soils in which the space between individual particles is completely filled with water. This water exerts a pressure on the soil particles that influences how tightly the particles themselves are pressed together. Prior to an earthquake, the water pressure is relatively low. However, earthquake shaking can cause the water pressure to increase to the point where the soil particles can readily move with respect to each other.

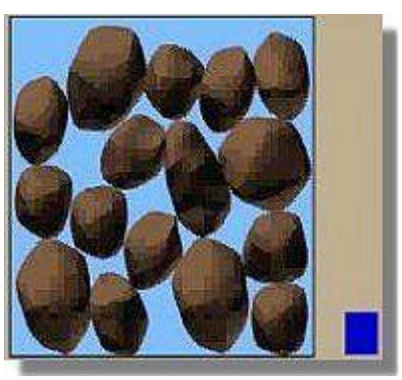
Earthquake shaking often triggers this increase in water pressure, but construction related activities such as blasting can also cause an increase in water pressure.

When liquefaction occurs, the strength of the soil decreases and, the ability of a soil deposit to support foundations for buildings and bridges is reduced as seen in the photo of the overturned apartment complex buildings in Niigata in 1964.

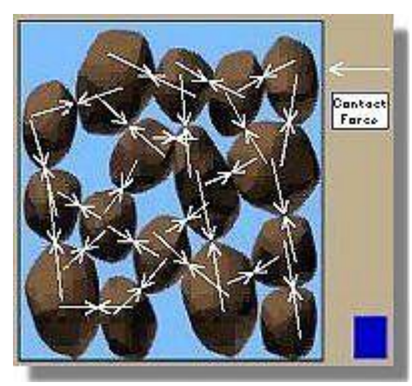
Because liquefaction only occurs in saturated soil, its effects are most commonly observed in low-lying areas near bodies of water such as rivers, lakes, bays, and oceans. The effects of liquefaction may include major sliding of soil toward the body slumping and of water.

Liquefaction also frequently causes damage to bridges that cross rivers and other bodies of water. Such damage can have drastic consequences, impeding emergency response and rescue operations in the short term and causing significant economic loss from business disruption in the longer term.

To understand liquefaction, it is important to recognize the conditions that exist in a soil deposit before an earthquake. A soil deposit consists of an assemblage of individual soil particles. If we look closely at these particles, we can see that each particle is in contact with a number of neighboring particles. The weight of the overlying soil particles produce contact forces between the particles - these forces hold individual particles in place and give the soil its strength.



Soil grains in a soil deposit. The height of the blue column to the right



The length of the arrows represent the size of the contact forces between individual represents the level of porewater pressure in the soil.

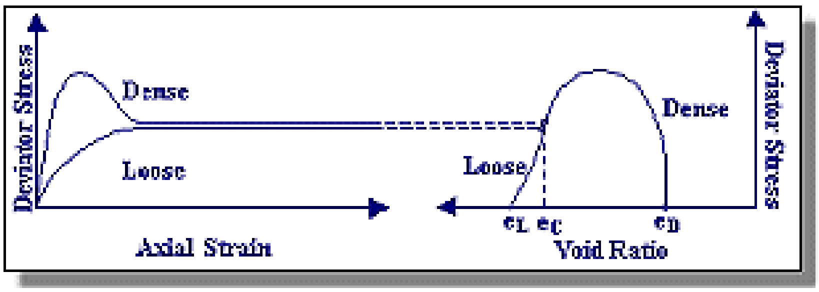
soil grains. The contact forces are large when the porewater pressure is low.

Liquefaction occurs when the structure of a loose, saturated sand breaks down due to some rapidly applied loading. As the structure breaks down, the loosely-packed individual soil particles attempt to move into a denser configuration. In an earthquake, however, there is not enough time for the water in the pores of the soil to be squeezed out. Instead, the water is "trapped" and prevents the soil particles from moving closer together. This is accompanied by an increase in water pressure which reduces the contact forces between the individual soil particles, thereby softening and weakening the soil deposit.

Observe how small the contact forces are because of the high water pressure. In an extreme case, the pore water pressure may become so high that many of the soil particles lose contact with each other. In such cases, the soil will have very little strength, and will behave more like a liquid than a solid - hence, the name "liquefaction".

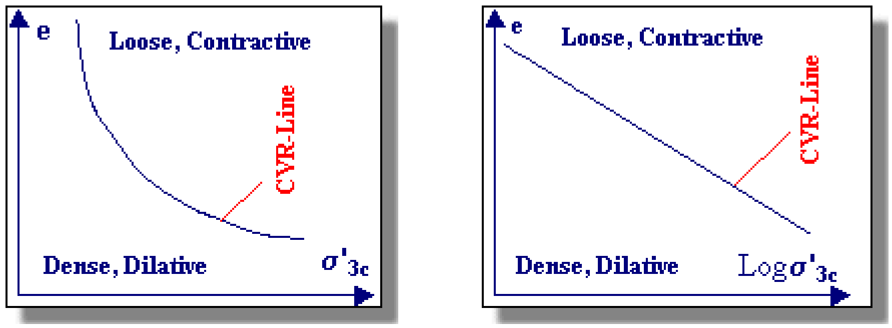
Critical Void Ratio

In 1936, Dr. Arthur Casagrande performed a series of drained strain-controlled triaxial tests and discovered that initially loose and dense specimens at the same confining pressure approached the same density when sheared to large strains. The void ratio corresponding to this density was called the critical void ratio (e_c).



Behavior of dense and loose soils in monotonic strain controlled triaxial tests (after Kramer, 1996).

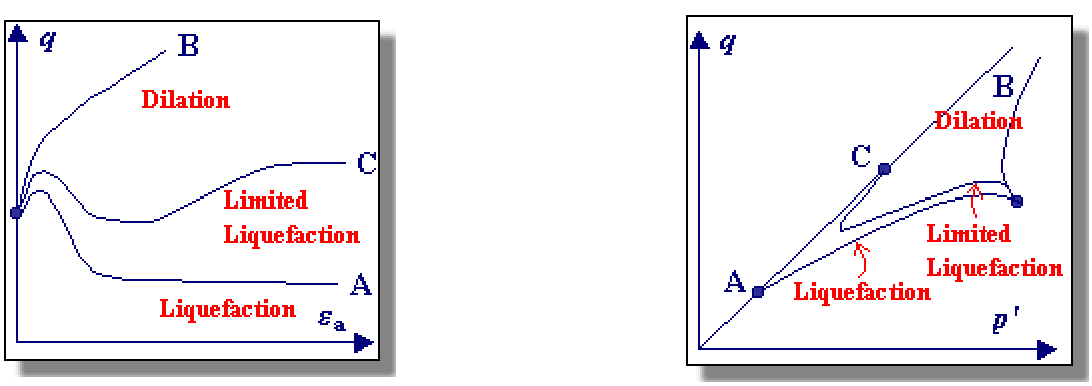
Performing tests at various effective confining pressures, Casagrande found that the critical void ratio varied with effective confining pressure. Plotting these on a graph produced a curve which is referred to as the critical void ratio (CVR) line. The CVR line constituted the boundary between dilative and contractive behavior in drained triaxial compression. A soil in a state that plots above the CVR line exhibits contractive behavior and vice versa (see figure below).

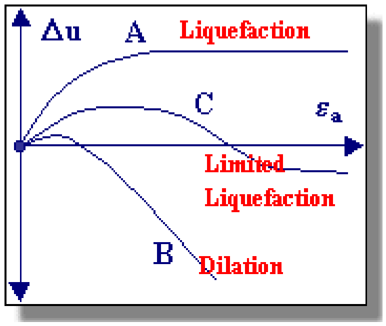


CVR-line for arithmetic and logarithmic confining pressure.

Steady State of Deformation

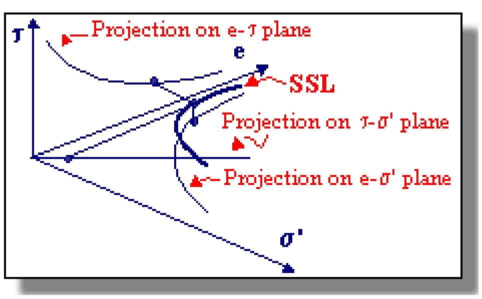
In the mid-1960s, Gonzalo Castro, a student of Casagrande, performed an important series of undrained, stress-controlled triaxial tests. Castro observed three different types of stress-strain behavior depending upon the soil state. Dense specimens initially contracted but then dilated with increasing effective confining pressure and shear stress. Very loose samples collapsed at a small shear strain level and failed rapidly with large strains. Castro called this behavior "liquefaction" - it is also commonly referred to as flow liquefaction. Medium dense soils initially showed the same behavior as the loose samples but, after initially exhibiting contractive behavior, the soil "transformed" and began exhibiting dilative behavior. Castro referred to this type of behavior as "limited liquefaction".

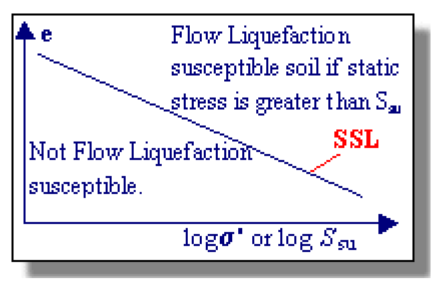




Static triaxial test stress paths for three specimens of different densities.

Castro plotted the relationship (see figure below) between effective confining pressure and void ratio at large strains for these undrained, stress-controlled tests. Castro referred to the curved produced by this plot, which is similar to the CVR line for the drained strain controlled tests performed by Casagrande, as the Steady State Line (SSL). The difference between the CVR and SSL was attributed to the existence of what Casagrande called a "flow structure", in which the grains orient themselves so the least amount of energy is lost by frictional resistance during flow.





Left: 3-D steady state line. Right: 2-D Projection of SSL plotted on graph of void ratio versus the logarithm of confining pressure or steady state strength.

As seen above, the SSL is actually a 3-dimensional curve in e- ▪'-▪ space. Using the 2-D projection on the e-▪' plane (see figure above), one can determine if a soil is susceptible to flow liquefaction. Soils in an initial state that plots below the SSL are not susceptible to flow liquefaction whereas soils plotting above the SSL are susceptible to flow liquefaction - **if** (and only if) the static shear stress exceeds the residual strength of the soil. Cyclic mobility, another liquefaction-related phenomenon, can occur in dense as well as loose soils.

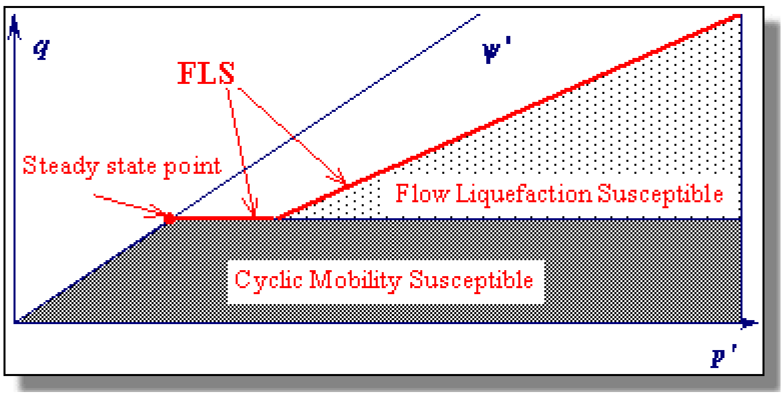
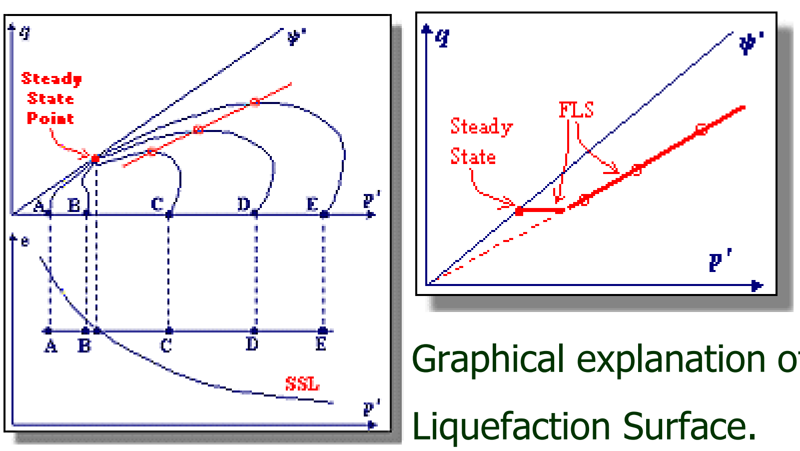


Figure showing zones of flow liquefaction and cyclic mobility susceptibility.

Flow Liquefaction

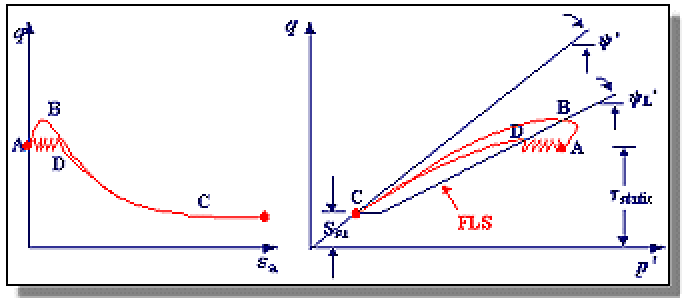
Flow liquefaction is a phenomenon in which the static equilibrium is destroyed by static or dynamic loads in a soil deposit with low residual strength. Residual strength is the strength of a liquefied soil. Static loading, for example, can be applied by new buildings on a slope that exert additional forces on the soil beneath the foundations. Earthquakes, blasting, and pile driving are all example of dynamic loads that could trigger flow liquefaction. Once triggered, the strength of a soil susceptible to flow liquefaction is no longer sufficient to withstand the static stresses that were acting on the soil before the disturbance.

On the left below is a plot of stress paths for five undrained shear tests. Three test specimens (C, D, and E) were subjected to loads greater than their residual strengths, and experienced flow liquefaction. A straight line (shown in red in the figure) drawn through the points where flow liquefaction was initiated projects back through the origin. This line is called the Flow Liquefaction Surface (FLS). Since flow liquefaction cannot take place if the static shear stress is lower than the steady state strength, the FLS is truncated by a horizontal line through the steady state point (see right figure below).The steady state strength is the strength a soil has when undergoing a steady state of deformation, i.e. continuous flow under constant shear stress and constant effective confining pressure at constant volume and constant velocity. Flow liquefaction will be initiated if the stress path crosses the FLS during undrained shear regardless of whether the loading is cyclic or monotonic loading (Vaid and Chern, 1983).



Graphical explanation of Flow Liquefaction Surface.

The stress paths for monotonic and cyclic loading can be seen below. The flow liquefaction process can be described in two stages. First, the excess pore pressure that develops at low strains moves the effective stress path to the FLS, at which point the soil becomes unstable. When the soil reaches this point of instability under undrained conditions, its shear strength drops to the residual strength. As a result the static shear stresses drive the large strains that develop as the soil "collapses". A great amount of strain-softening takes place when the stress path moves toward the steady state point.

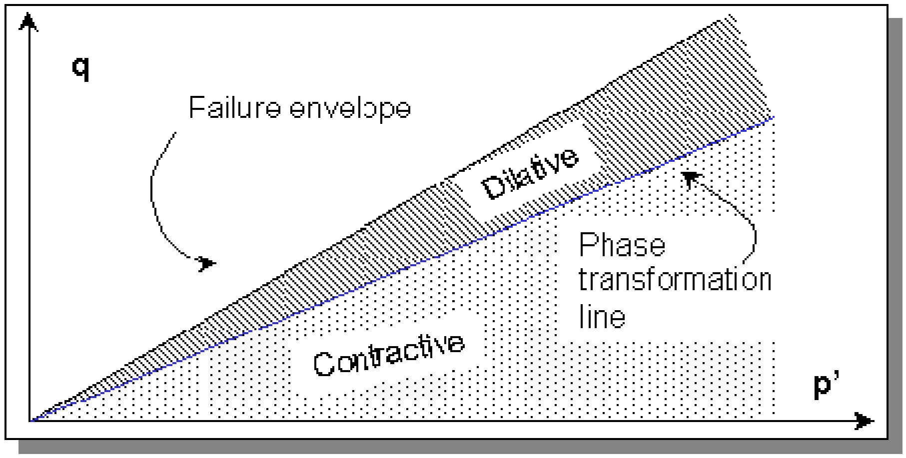


Flow Failure induced by cyclic and monotonic loading.

Cyclic Mobility

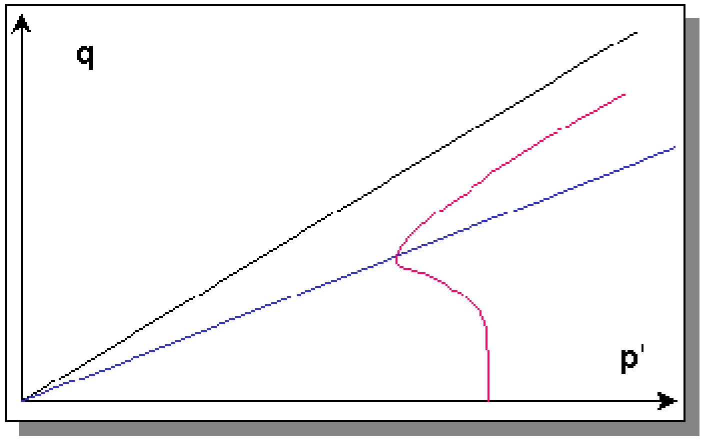
Cyclic mobility is a liquefaction phenomenon, triggered by cyclic loading, occurring in soil deposits with static shear stresses lower than the soil strength. Deformations due to cyclic mobility develop incrementally because of static and dynamic stresses that exist during an earthquake. Cyclic mobility can occur even when the static shear stress is lower than the steady state (or residual) shear strength.

A key to this understanding came about with identification of the phase transformation line. Medium dense to dense sands subjected to monotonic loading will initially exhibit contractive behavior, but then exhibit dilative behavior as they strain toward the steady state. A plot of the stress path points at which the transformation from contractive to dilative behavior takes place reveals a phase transformation line (PTL) that appears to project back through the origin (Ishihara, 1985).



A p'-q plot of the phase transformation line

In the contractive region, an undrained stress path will tend to move to the left as the tendency for contraction causes pore pressure to increase and p' to decrease. As the stress path approaches the PTL, the tendency for contraction reduces and the stress path becomes more vertical. When the stress path reaches the PTL, there is no tendency for contraction or dilation, hence p' is constant and the stress path is vertical. After the stress path crosses the PTL, the tendency for dilation causes the pore pressure to decrease and p' to increase, and the stress path moves to the right.



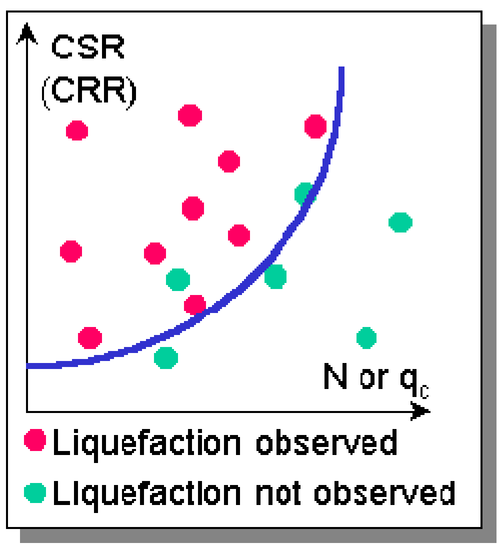
A stress path example.

Note that, because the stiffness of the soil depends on p', the stiffness decreases (while the stress path is below the PTL) but then increases (when the stress path moves above the PTL). This change in stiffness produces the "limited liquefaction" behavior originally noted by Castro.

Under cyclic loading conditions, the behavior becomes even more complex. Remembering that the failure envelope and PTL exist for negative shear stresses as well as positive, it is easy to see that a cyclically loaded soil can undergo the contraction/dilation transformation in two different directions. The stress-strain and stress path plots for a harmonically loaded element of soil will therefore show softening behavior in the early stages of loading (before the stress path has reached the PTL) but then show cyclic softening and hardening as the stress path moves from one side of the PTL to the other. The result of the phase transformation behavior is reflected in the development of "banana-shaped" stress-strain loops.

Evaluation of Liquefaction Potential

Evaluation of the potential for liquefaction to occur is accomplished by comparing equivalent measures of earthquake loading and liquefaction resistance. The most common approach to characterization of earthquake loading is through the use of cyclic shear stresses. By normalizing the cyclic shear stress amplitude by the initial effective vertical stress, a cyclic stress ratio (CSR) can represent the level of loading induced at different depths in a soil profile by an earthquake. There are different procedures for evaluating the cyclic shear stresses - site response analyses may be performed or a "simplified" approach may be used to estimate CSR as a function of peak ground surface acceleration amplitude.



[

CSR versus N or q_c

Liquefaction resistance is most commonly characterized on the basis of observed field performance. Detailed investigation of actual earthquake case histories has allowed determination of the combinations of insitu properties (usually SPT or CPT resistance) and CSR for each case history. By plotting the CSR-(N1)60 (or CSR-qc) pairs for cases in which liquefaction was and was not been observed, a curve that bounds the conditions at which liquefaction has historically been observed can be drawn. This curve, when interpreted as the maximum CSR for which liquefaction of a soil with a given penetration resistance can resist liquefaction, can be thought of as a curve of cyclic resistance ratio (CRR). Then, the potential for liquefaction can be evaluated by comparing the earthquake loading (CSR) with the liquefaction resistance (CRR) - this is usually expressed as a factor of safety against liquefaction,

FS = CRR / CSR

A factor of safety greater than one indicates that the liquefaction resistance exceeds the earthquake loading, and therefore that liquefaction would not be expected.

There are basically three possibilities to reduce liquefaction hazards when designing and constructing new buildings or other structures as bridges, tunnels, and roads.

Avoid Liquefaction Susceptible Soils

The first possibility, is to avoid construction on liquefaction susceptible soils. There are various criteria to determine the liquefaction susceptibility of a soil. By characterizing the soil at a particular building site according to these criteria one can decide if the site is susceptible to liquefaction and therefore unsuitable for the desired structure. Learn more about liquefaction susceptibility.

Build Liquefaction Resistant Structures

If it is necessary to construct on liquefaction susceptible soil because of space restrictions, favorable location, or other reasons, it may be possible to make the structure liquefaction resistant by designing the foundation elements to resist the effects of liquefaction. Learn more about design of liquefaction resistant structures.

Improve the Soil

The third option involves mitigation of the liquefaction hazards by improving the strength, density, and/or drainage characteristics of the soil.

Earthquake Hazard and Risk

Hazard and risk are fundamentally different. **Hazard** is a phenomenon that has potential to cause harm. Phenomena are both natural and man-made. For example, earthquakes, hurricanes, tornadoes, and floods are natural hazards; whereas car crashes, chemical spills, train derailments, and terror attacks are man-made hazards.

Risk , on the other hand, is the likelihood (chance) of harm if someone or something is exposed to a hazard, and generally quantified by three terms: likelihood (chance), a level of hazard (loss), and exposure (time).

Seismic Hazard: Earthquakes of a certain magnitude or the phenomena generated by the earthquakes, such as surface rupture, ground motion , ground-motion amplification , liquefaction , and induced-landslides, that have potential to cause harm.

Seismic Risk: Likelihood (chance) of experiencing a level of seismic hazard for a given exposure (time and asset).

The relationship between seismic hazard and risk is complicated and must be treated very cautiously. Seismic hazards are natural occurrences and can be evaluated from instrumental, historical, and geological records (or observations).

Seismic risk depends not only on seismic hazard and exposure, however, but also on the models (i.e., time-independent [Poisson] and time-dependent ones) that could be used to describe the occurrences of earthquakes.

High seismic hazard does not necessarily mean high seismic risk, and vice versa. On the other hand, the seismic risk could be high in some areas, such as Pakistan and Iran , because of high exposures, even though the hazards are moderate.

The common model being used to describe earthquake occurrences is the Poisson distribution (time-independent: independent of the history of previous earthquakes). Other time-dependent earthquake occurrence models have also been used in seismic risk analyses. These different models will result in different risk estimates.

Assessing seismic hazards and risk is difficult because of insufficient data (records). This lack of data results in large uncertainties for the seismological parameters that are the basis for assessing seismic hazards and risk.

Seismic hazards can be assessed either by probabilistic seismic hazard analysis (PSHA) or deterministic seismic hazard analysis (DSHA). The fundamental difference between PSHA and DSHA is in how the uncertainties are treated: either implicitly (PSHA) or explicitly (DSHA). Although PSHA has been more widely used.

Attenuation Relation

Attenuation is a decrease in the strength of seismic waves and seismic energy with distance from the point where the fault rupture originated.

$$I(R) = I0 + a + bR + C \log10 R$$

R : Radius of the Circle from Epicenter

I(R) : Intensity from distance R

a,b,c : Constants .

$$I(R) = I0 + 6.453 - 0.00121 R - 2.15 \ln (R+20)$$

$$I0 = 0.95 Ms + 1.99$$

Ignore 0.00121 R

$$I = 8.443 + 0.95 Ms - 2.15 \ln (R+20)$$

EQ. Ground Response.

Peak ground Acceleration (PGA) 1.

$$Log(PGA)\ h=0.57+0.5\ mb-0.83\ log(R^2+h^2{}_m)^{1/2} - 0.00069R$$

R: Hypocentral Distance

h_m : Minimum Focal depth

$$Hm = -1.73 + 0.456\ mb \qquad mb > 4.5$$

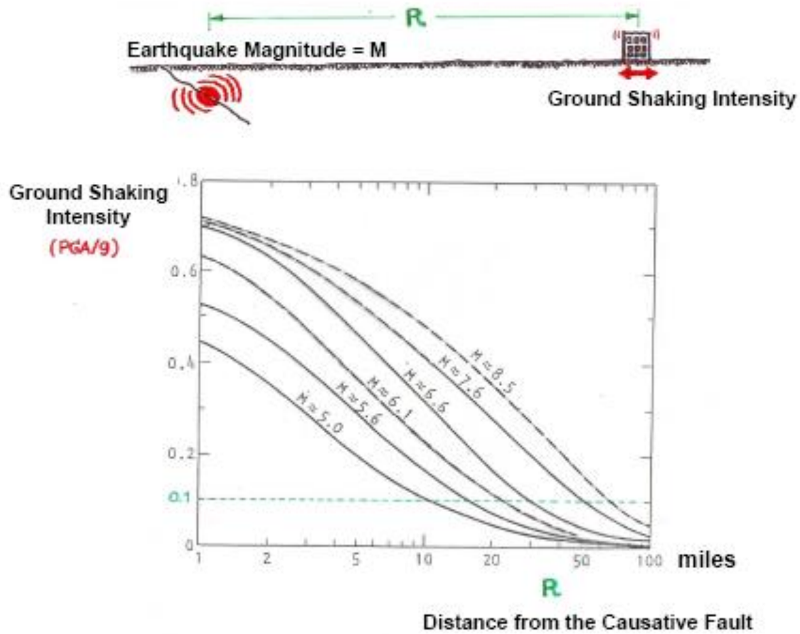
2. Peak Ground Velocity (PGV)

$$Log\ (PGV)_h = -3.6+1.0\ mb - 0.83\ Log(R^2 + h^2{}_m)^{1/2} - 0.00033R$$

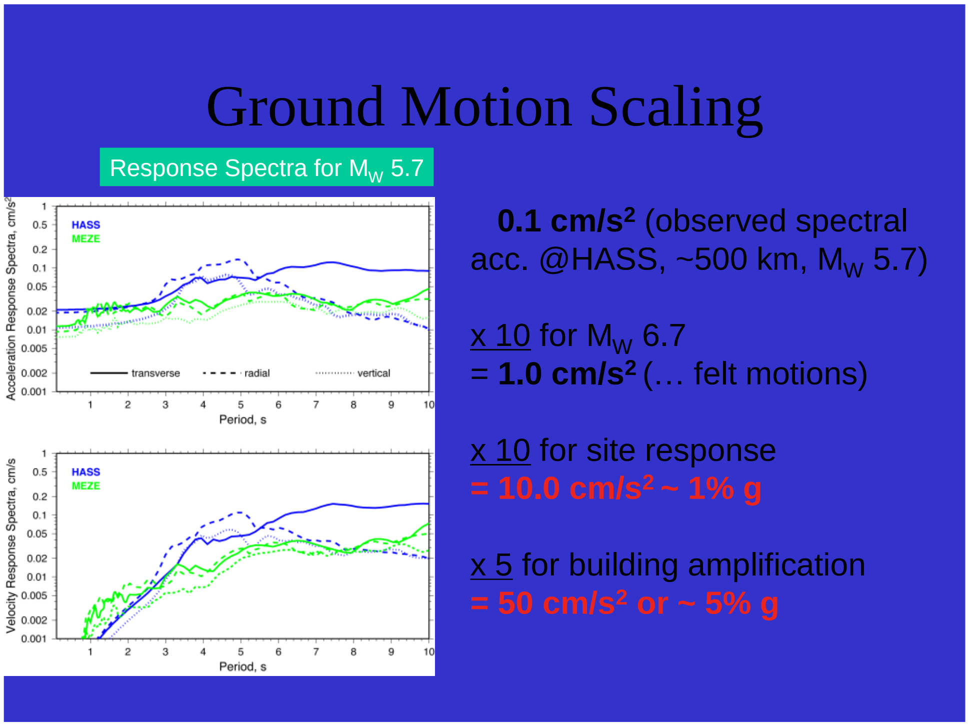
3. Peak ground Displacement

4. Spectral Characteristics

5. Duration



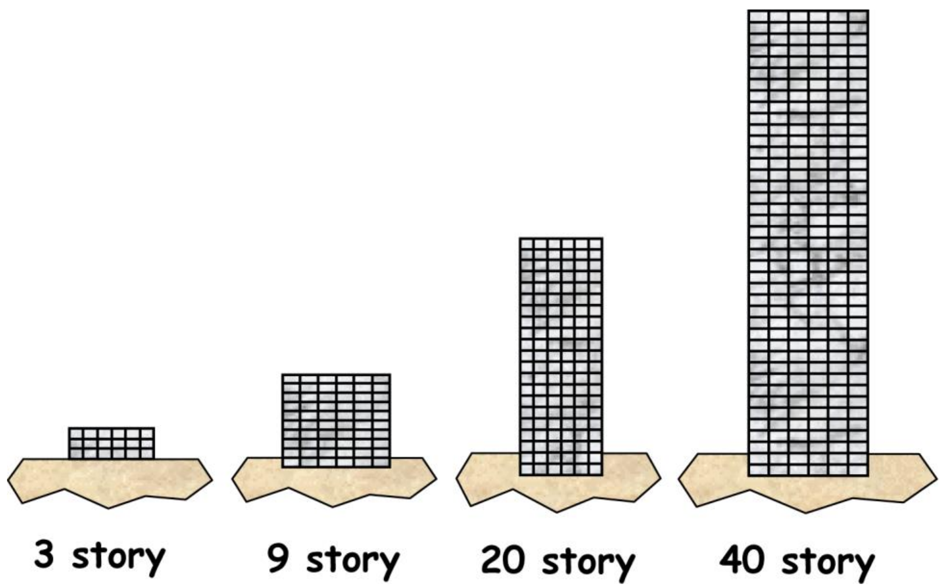
Inverse Relationship between the distance from fault and Intensity



Earthquake Engineering: Large Structures Are Susceptible to Long-Period Motions

Stories	Height	Period
1	5 m	0.1 s
3	15 m	0.3 s
10	44 m	1.0 s
20	86 m	2.0 s
40	166 m	4.0 s
100	540 m	10.0 s

Actual period is typically less for than these values for tallest buildings because they are more stiff.



Natural (resonant) period of a building increases with building height.

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 :

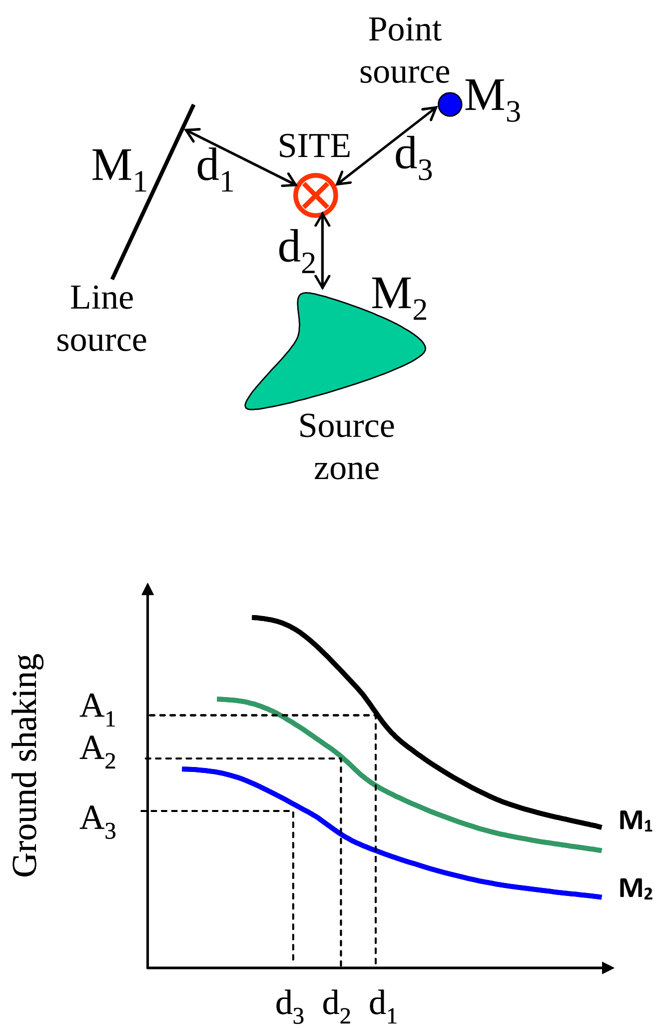
1. Identification and characterization of all earthquake sources capable of producing significant ground motion at the site. Source characterization includes definition of each source's geometry (the source zone) and earthquake potential.

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

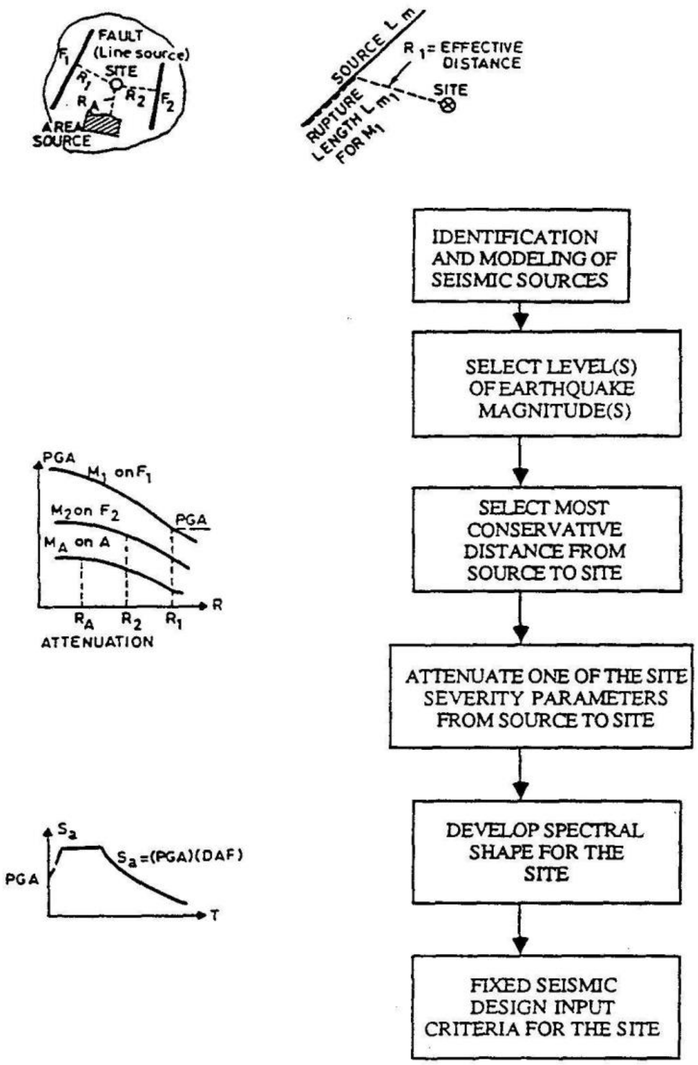
in terms of its size (usually expressed as magnitude) and distance from the site.

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.



Deterministic seismic hazard= $\max(A_1, A_2, A_3)$

Components of deterministic seismic hazard analysis.



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

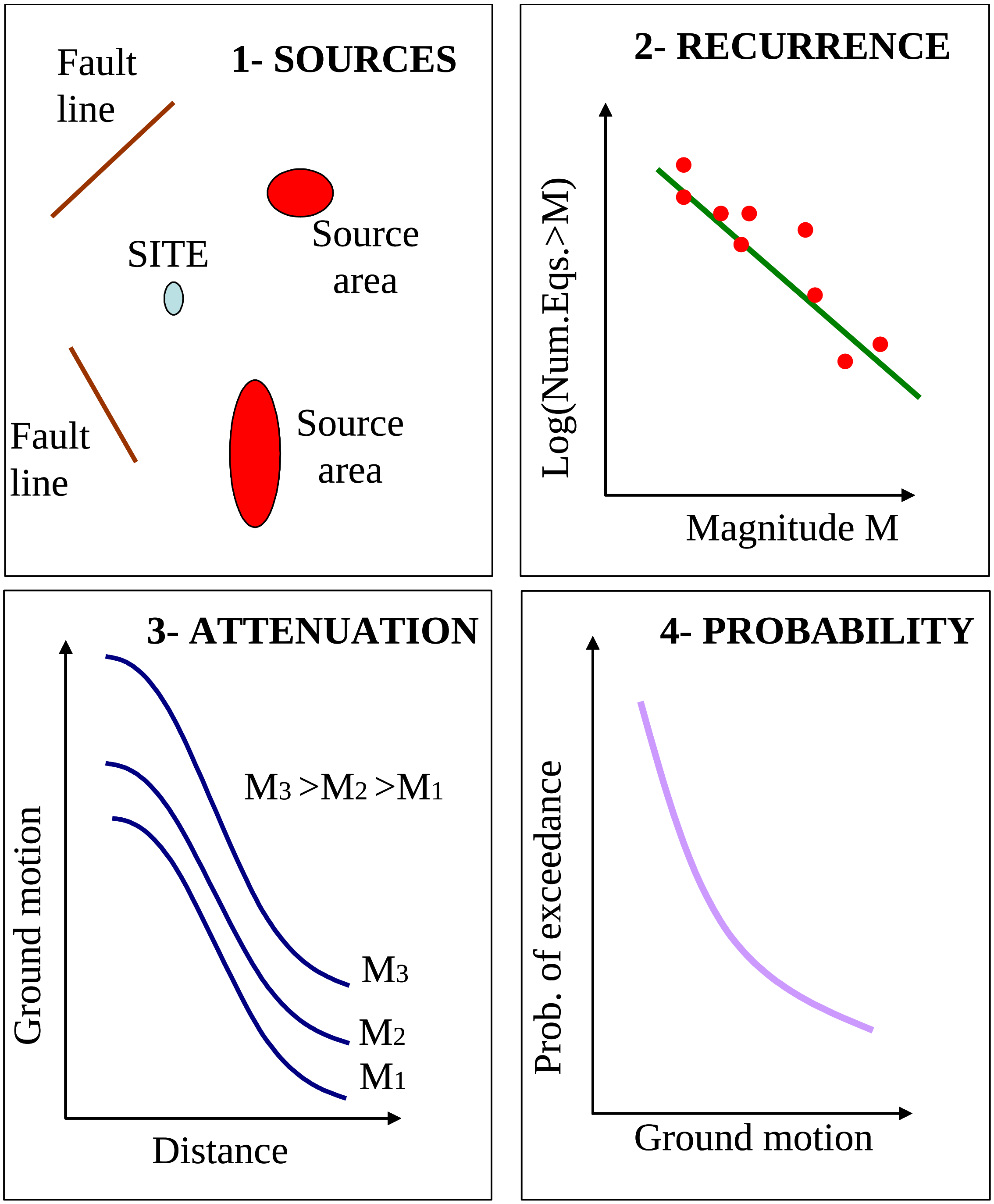
PROBABILISTIC SEISMIC HAZARD ANALYSIS

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.

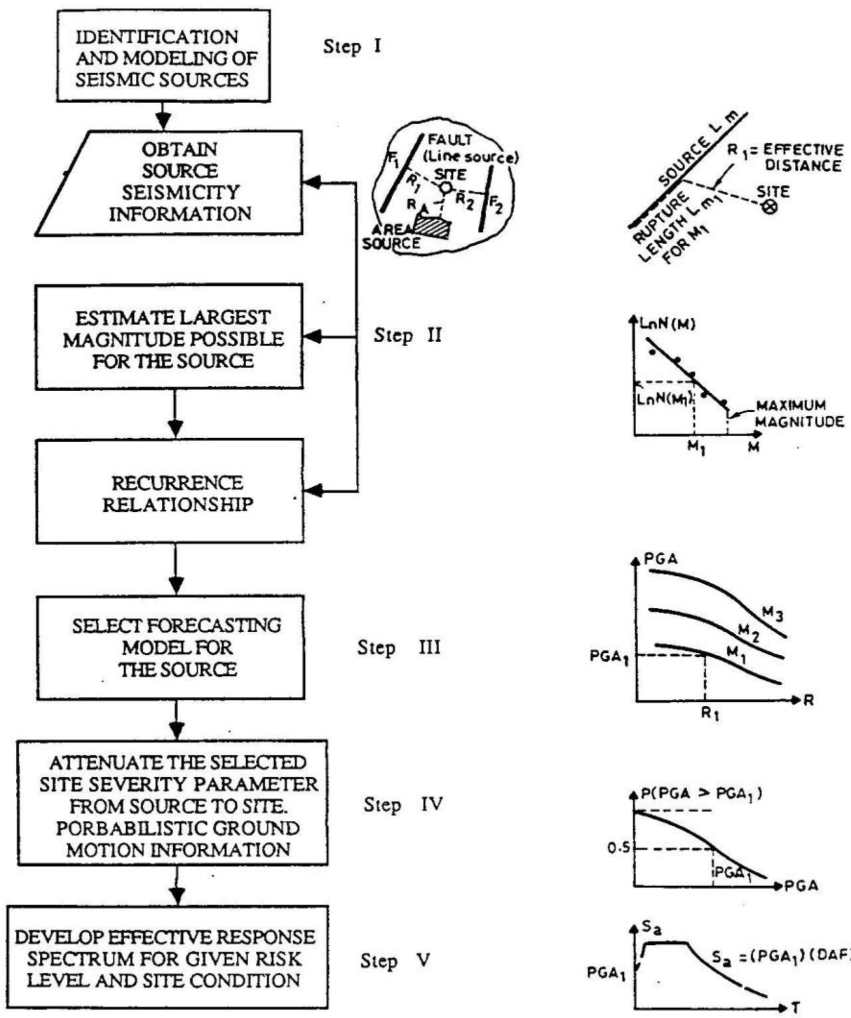
The PSHA can also be described as a procedure of four steps each of which bear some degree of similarity to the steps of the DSHA procedure (Reiter, 1990) :

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.



Steps of probabilistic seismic hazard analysis for a given site: (1) definition of earthquake sources, (2) earthquake recurrence characteristics for each source, (3) attenuation of ground motions with magnitude and distance, and (4) ground motions for specified probability of exceedance levels (calculated by summing probabilities over all the sources, magnitudes, and distances).



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:

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

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):

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

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:

$$\lambda_m = v \frac{\exp[-\beta(m - m_o)] - \exp[-\beta(m_{max} - m_o)}{1 - \exp[-\beta (m_{max} - m_o)]} \quad m_o \leq m \leq m_{max} \quad (5)$$

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

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

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

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:

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

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

$$\mathbf{P[N \geq 1 , t] = P[N = 1] + P[N = 2] + P[N = 3] + ...}$$

$$\mathbf{+ P[N = \omega] = 1 - P(N= 0,t] = 1 - \exp (-\lambda t)} \qquad \mathbf{(9)}$$

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,

$$\mathbf{f(t) = \lambda_m \exp(-\lambda_m t) \qquad t \geq 0}$$

$$\mathbf{= 0,\ Otherwise} \qquad \mathbf{(11)}$$

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

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

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
$\mathbf{\lambda_m T_R = 1}$

and hence $\mathbf{T_R = 1/\,\lambda_m}$ **(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

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

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

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

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

Al-Zaid, R. (1988). Seismic Hazard Analysis and Specification of Ground Motion. Short course on " Earthquake Engineering ", Dept. of Civil Engineering, King Saud Univ.

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:

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

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:

$$f_1(M) = \exp(b_2 M)$$

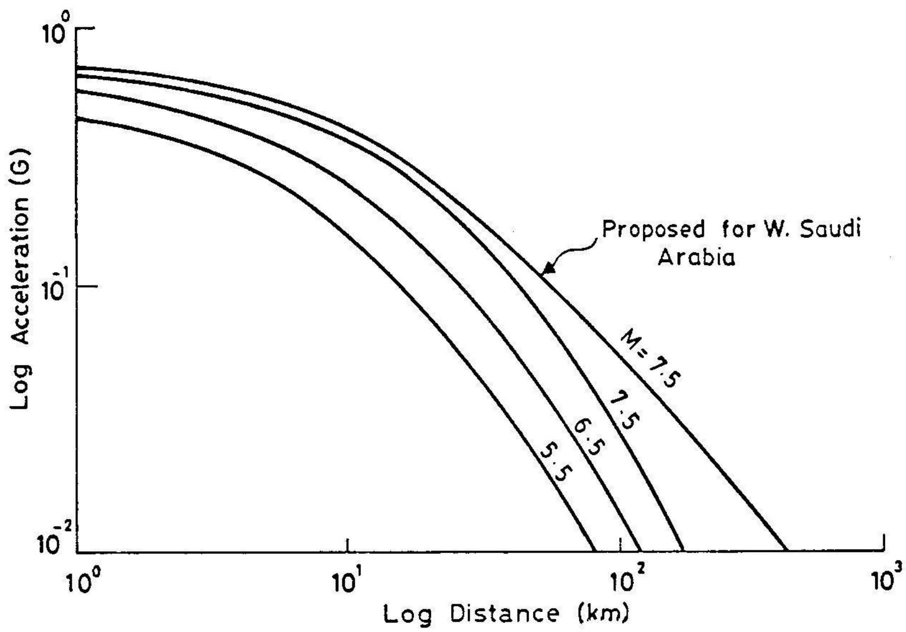
$f_2(R)$ is a function of the distance R, the most common form being:

$f_2(R) = \exp(b_4 R)(R + b_5)^{-b3}$, 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).

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

where b_1 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_u 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:

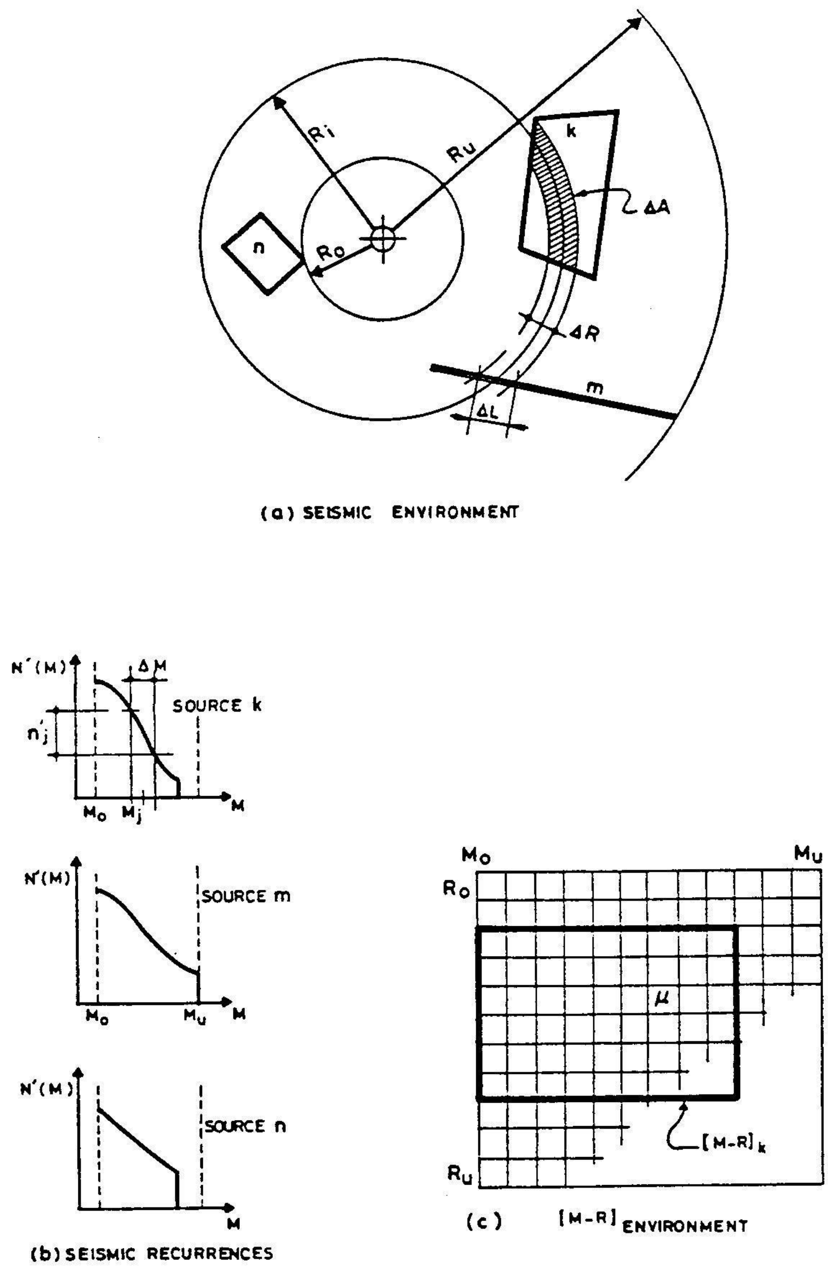
$$\mathbf{n_{jk} = N_{\mathit{k}} (M_j - \Delta M/ 2) - N_{\mathit{k}} (M_j + \Delta M/ 2)}$$
(3)

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:

$$\lambda_{ijk} = n_{jk} \; \Delta A_{ik} \text{ for area sources, and}$$
$$\lambda_{ijk} = n_{jk} \; \Delta L_{ik} \text{ for line sources} \qquad (4)$$

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 $[M\text{-}R]_k$ 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,

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

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,

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

(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:

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

a_{min} = $f(R_u, Mo)$, 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,

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

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.

Al-Zaid, R. (1988). Hazard Curves at Specific Sites and Zonation map of the Kingdom. Short course on " Earthquake Engineering ", Dept. of Civil Engineering, King Saud Univ.

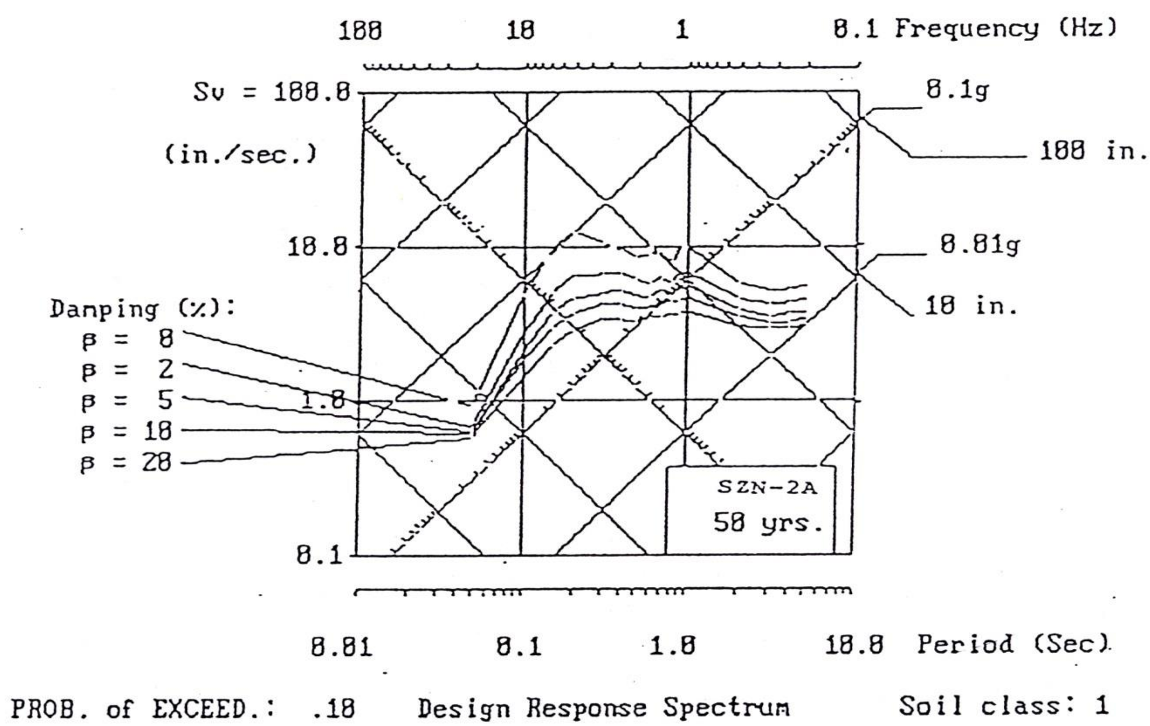


Fig. 3 Response Spectrum for a Site in Zone 2A for Probability of Exceeding of 10% in 50 years .

شكل رقم (٣) طيف الإستجابة لموقع بالمنطقة رقم (2A) لإحتمال تجاوز ١٠ ٪ خلال ٥٠ عام

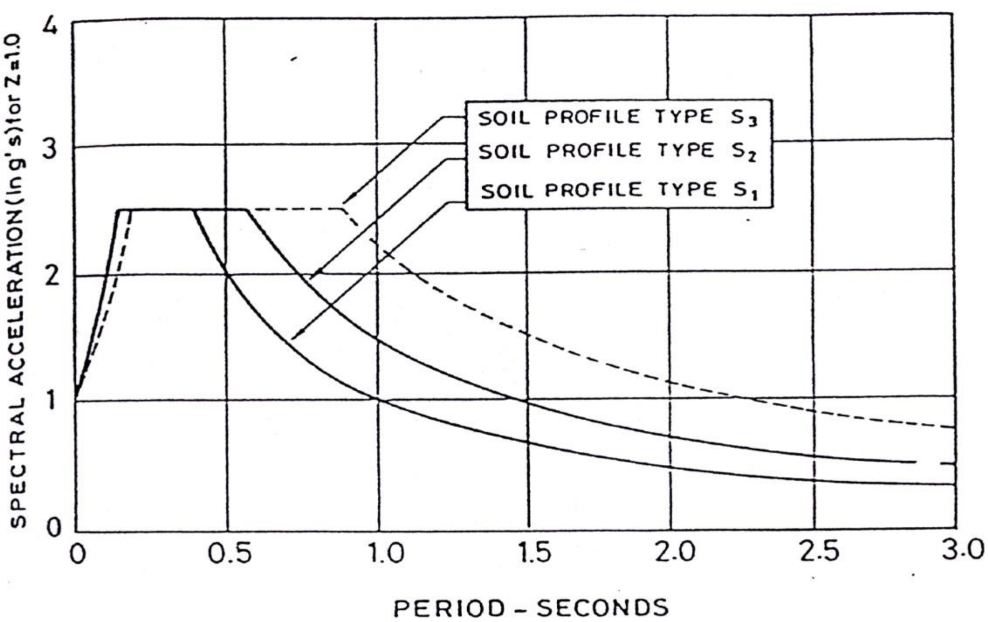


Fig. 5 : Response Spectra Normalized for Z=1.0 For 5% Damping.

شكل رقم (٥) طيف الإستجابة الطبيعي لـ (Z) = ١ ٪ تجاوز و ٥ ٪ تهدم

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:

$$\text{Log Mo} = [(1.62 \pm 0.112)\text{Ms} + 15.1] \pm 0.3 \quad (2)$$

$$\text{Log Mo} = [(2.54 \pm 0.087)\text{Log L} + 22.56] \pm 0.31 \quad (3)$$

$$\text{Log Mo} = [(2.61 \pm 0.28)\text{Log D} + 26.32] \pm 0.44 \quad (4)$$

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

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

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

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)

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

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

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

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

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)

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

A = exp[(a + bc/d)ln10]

$$\mathbf{B = b/d}$$

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

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

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

$$\mathbf{Mo(tot)= B/(1\text{-}B)Mo(max)} \qquad \mathbf{(12)}$$

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

$$\mathbf{T(max) = Mo(tot)/Mo(g)} \qquad \mathbf{(13)}$$

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

$$T(max) = D/S \tag{14}$$

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).

$$Ms = 1.14\ Mb - 0.9 \tag{15}$$

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

$$Mmax(H) = 4 \log H + 1.8 \quad (16)$$

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

$$Pr = 1 - \exp(-t / Tmax) \quad (17)$$

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 .

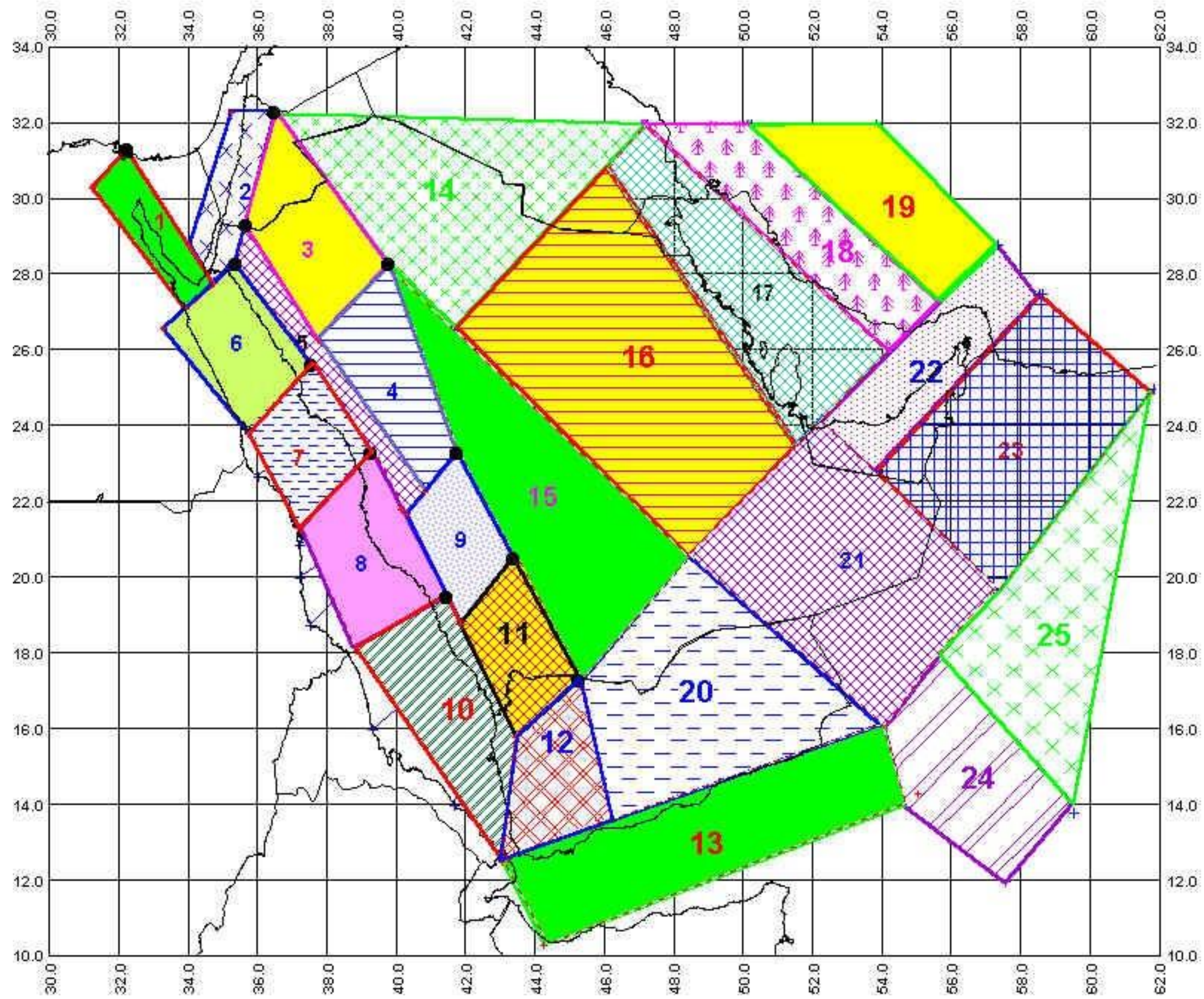
SEISMIC SOURCE ZONES

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 Source Zones of the Arabian Peninsula and Adjoining Regions

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:

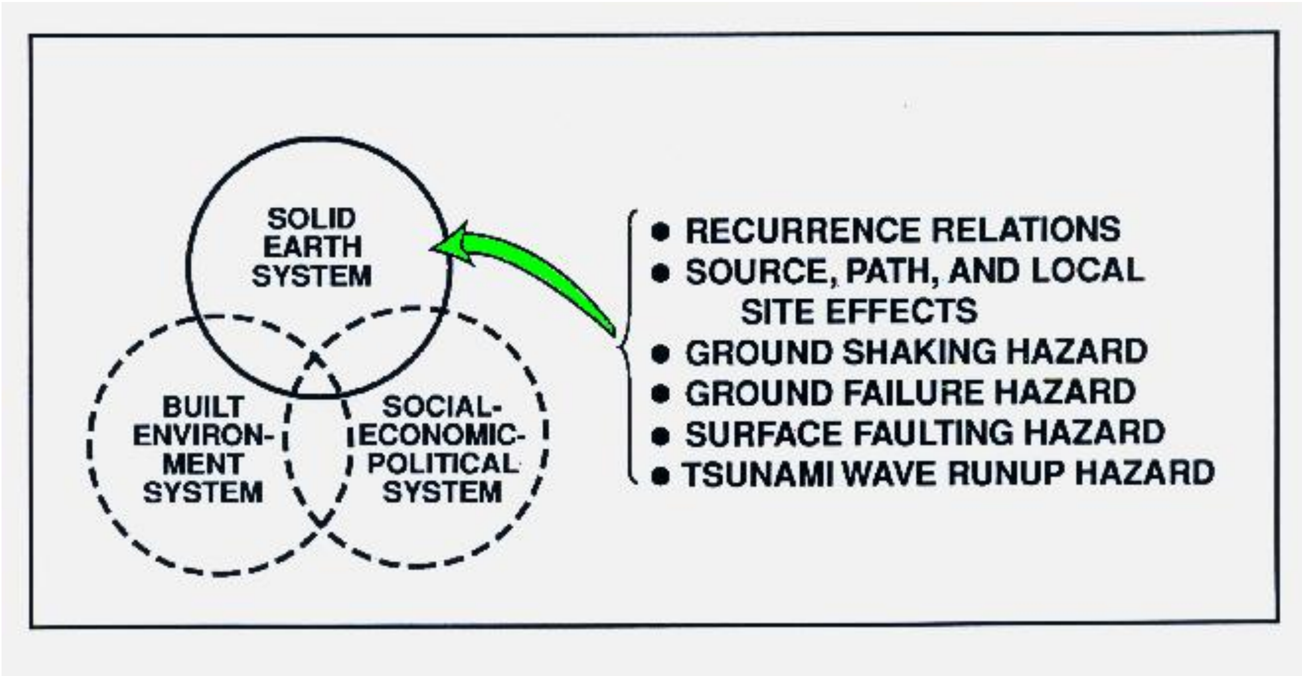
1. **Solid Earth System** (i.e., defines the physical characteristics of the source, path, and site which control earthquake hazards (e.g., ground shaking and ground failure hazards)).
   - Where have earthquakes occurred in the past?
   - Where are they occurring now?
   - What is the magnitude and 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?


SOLID
EARTH
SYSTEM
BUILT
ENVIRON-
MENT
SYSTEM
SOCIAL-
ECONOMIC-
POLITICAL
SYSTEM
• RECURRENCE RELATIONS
• SOURCE, PATH, AND LOCAL SITE EFFECTS
• GROUND SHAKING HAZARD
• GROUND FAILURE HAZARD
• SURFACE FAULTING HAZARD
• TSUNAMI WAVE RUNUP HAZARD

REDUCTION OF COMMUNITY VULNERABILITY

BUILT ENVIRONMENT

- Location value, exposure, and vulnerability of buildings lifelines at risk from earthquake physical effects (hazards) w can cause damage, failure, loss of function, release of hazar 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 earthquake and the aftershock sequence; each potentially impacting the built environment.	*Social, technical, Administrative, political, legal, and economic forces which shape a community's policies and practices for: earthquake risk management (i.e., prevention, mitigation, preparedness, prediction and warning, intervention, emergency), public awareness, training, education, and insurance.

The Status of Seismic Zonation

Types of zonation Maps Being Produced

und motion

Intensity **Peak acceleration**

Peak velocity **Spectral response**

With consideration of the potential for soil amplification by the following types of soils:

 # S1 # S2 # S3 # S4

Ground Failure

@ Liquefaction @ Lateral spreads @ Landslides

Flood Waves

$ Tsunami $ Seiche

Applications

To stop Increasing the Risk

- Building Codes
- Land Use Ordinances
- Urban / Regional Development Plans

To start Decreasing the Risk

- Structural Strengthening
- Non – structural detailing

- **To Continue Planning for the Inevitable**
- Scenarios for Emergency Response
- Scenarios for Recovery and construction

Seismic Risk Assessment

A seismic risk assessment is defined as the evaluation of potential economic losses, loss of function, loss of confidence, fatalities, and injuries from earthquake hazards. Given the current state of knowledge of seismic phenomena, little can be done to modify the hazard by controlling tectonic processes, but there are a variety of ways to control the risk or exposure to seismic hazards.

There are four steps involved in conducting a seismic risk assessment:

(1) an evaluation of earthquake hazards and prepare hazard zonation maps;

(2) an inventory of elements at risk, e.g., structures and population;

(3) a vulnerability assessment; and

(4) determination of levels of acceptable risk.

(1) Evaluating Earthquake Hazards and Hazard Zonation Maps

In an earthquake-prone area, information will undoubtedly exist on past earthquakes and associated seismic hazards. This can be supplemented with existing geologic and geophysical information and field observation, if necessary. Depending on geologic conditions, some combination of ground shaking, surface faulting, landslides, liquefaction, and flooding which may be the most serious potential earthquake-related hazards in an area. Maps should be prepared showing zones of these hazards according to their relative severity. These maps provide the planner with data on such considerations as the spatial application of building codes and the need for local landslide and flood protection.

(a) Assessing Ground Shaking Potential: Even though ground shaking may cause the most widespread and destructive earthquake-related damage, it is one of the most difficult seismic hazards to predict and quantify. This is due to the amplification of the shaking effects by the unconsolidated material overlying the bedrock at a site and to the differential resistance of structures. Consequently, the ideal way to express ground shaking is in terms of the likely response of specific types of buildings. These are classified according to whether they are wood frame, single-story masonry, low-rise (3 to 5 stories), moderate-rise (6 to 15 stories), or high-rise (more than 15 stories). Each of these, in turn, can be translated into occupancy factors and generalized into land-use types.

Alternative approaches can be used for planning purposes to anticipate where ground shaking would be most severe:

- The preparation of intensity maps based on damage from past earthquakes rated

  according to the Modified Mercalli Index.

- The use of a design earthquake to compute intensity.

- In the absence of data for such approaches, the use of information on the causative fault,

distance from the fault, and depth of soil overlying bedrock to estimate potential damage.

(b) Assessing Surface Faulting Potential: This is relatively easy to do, since surface faulting is associated with fault zones. Three factors are important in determining suitable mitigation measures: probability and extent of movement during a given time period, the type of movement (normal, reverse, or slip faulting), and the distance from the fault trace in which damage is likely to occur.

In areas of active faulting, fault maps should be prepared at scales appropriate for planning purpose (about 1:50,000 in developing areas and 1:10,000 in urban areas) and kept updated as new geologic and seismic information becomes available. The extent on the areas in jeopardy along the faults should be determined, and maps should be prepared show in the degree of hazard in each of them. Measures such as land-use zonation and building restrictions should be prescribed for areas in jeopardy.

(c) Assessing Ground Failure Potential: This method is applicable to earthquake-induced landslides. Liquefaction potential is determined in four steps: (1) a map of recent sediments is prepared, distinguishing areas that are likely to be subject to liquefaction from those that are unlikely; (2) a map showing depth to groundwater is prepared; (3) these two maps are combined to produce a "liquefaction susceptibility" map; and (4) a "liquefaction opportunity" is prepared by combining the susceptibility map with seismic data to show the distribution of probability that liquefaction will occur in a given time period.

(2) Inventory of Elements at Risk

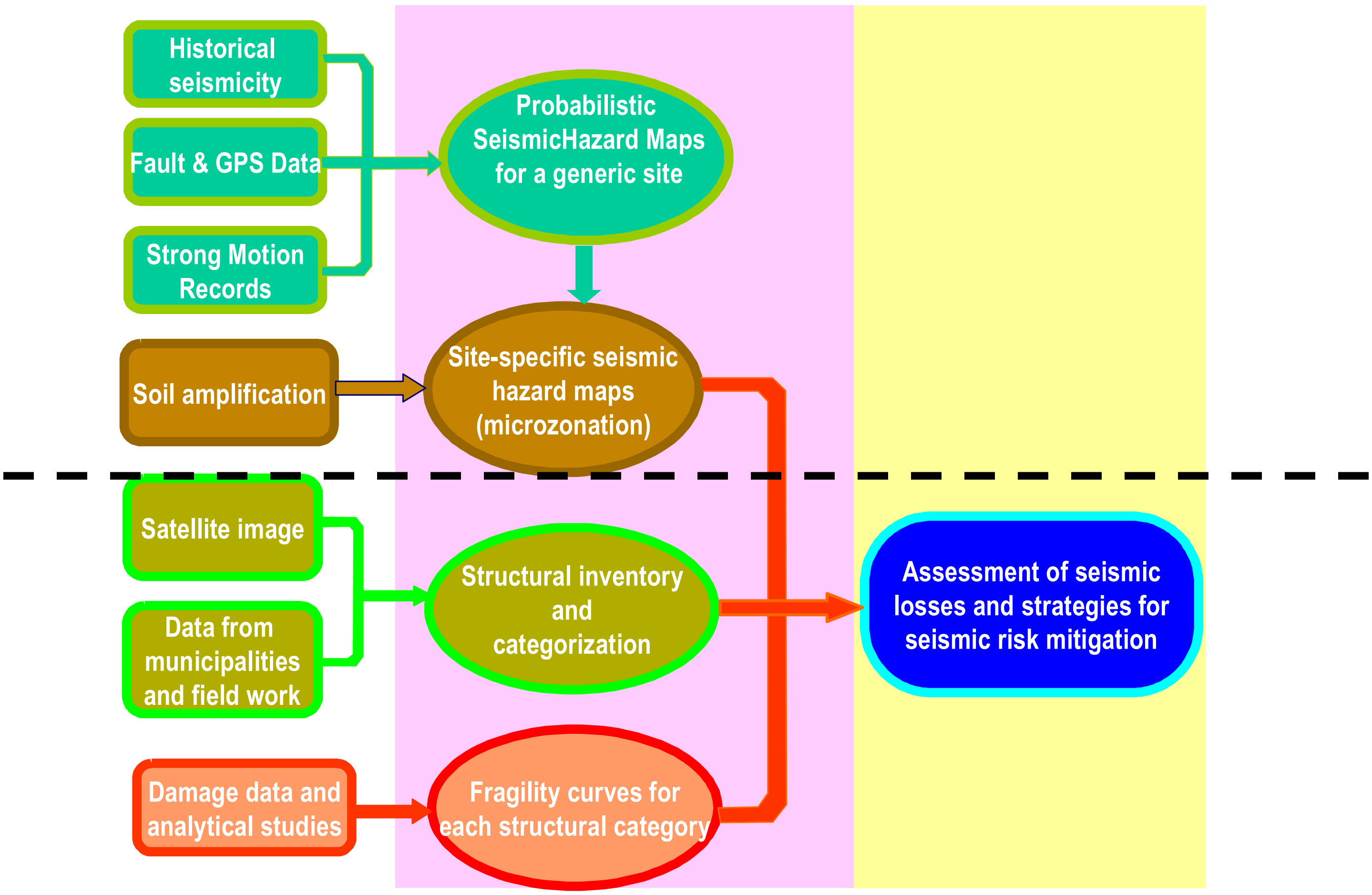
The inventory of elements at risk is a determination of the spatial distribution of structures and population exposed to the seismic hazards. It includes the built environment, e.g., buildings, utility transport lines, hydraulic structures, roads, bridges, dams; natural phenomena of value such as aquifers and natural levees; and population distribution and density. Lifelines, facilities for emergency response, and other critical facilities are suitably noted.

(3) Vulnerability Assessment

Once an inventory is available, a vulnerability assessment can be made. This will measure the susceptibility of a structure or class of structures to damage. It is difficult, if not impossible, to predict the actual damage that will occur, since this will depend on an earthquake's epicenter, size, duration, etc. The best determination can be made by evaluating the damage caused by a past earthquake with known intensity in the area of interest and relating the results to existing structures.

(4) Assessing Risk and Its Acceptability

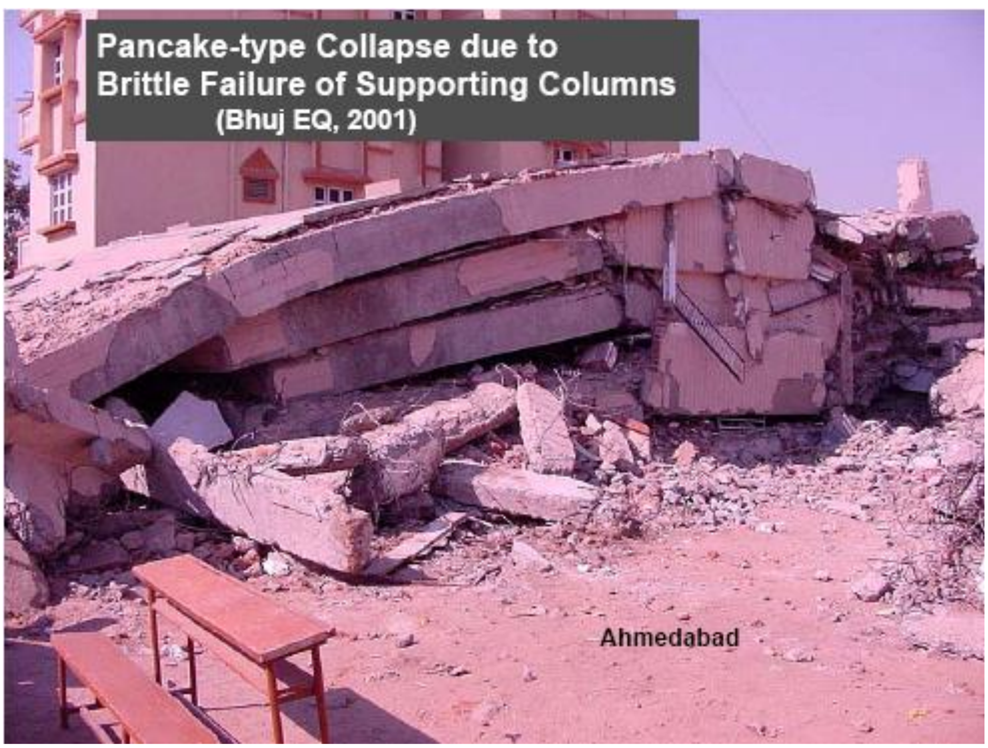
It is theoretically possible to combine the hazard evaluation with the determination of the vulnerability of elements at risk to arrive at an assessment of specific risk, a measure of the willingness of the public to incur costs to reduce risk. This is a difficult and expensive process, however, applicable to advanced stages of the development planning process. For any particular situation, planners and hazard experts working together may be able to devise suitable alternative procedures that will identify approximate risk and provide technical guidance to the political decisions as to what levels are acceptable and what would be acceptable costs to reduce the risk. Thus, the appropriate mitigation measures can be recommended as part of a development study.



Components of seismic hazard assessment and risk reduction.

CASE HISTORIES


Brittle Shear Failure of Supporting Columns (Chi Chi EQ, 1999)


Pancake-type Collapse due to
Brittle Failure of Supporting Columns
(Bhuj EQ, 2001)
Ahmedabad


Nonductile
reinforcement
details in column
Brittle failure in column

GLOSSARY

<u>Seismic Zonation</u> is the division of a geographic region into smaller areas or zones based on an integrated assessment of the hazard, built, and policy environments of the Nation, a region, or a community . Seismic zonation maps, which can be constructed on scales ranging from national to urban, provide decision makers with a scientific and technical basis for selecting prevention, mitigation, and preparedness options to cope with the physical phenomena generated in an earthquake (i.e., ground shaking, ground failure, surface fault rupture, regional tectonic deformation, tsunami run up, and aftershocks). Seismic zonation contributes to risk reduction and sustainability of new development. Seismic zonation maps are the result of a process that integrates data, results of research and post earthquake Investigations, and experiences on the hazard, built, and policy environments. The maps are used to answer questions decision makers and end users are asking about their communities, such as:

- Which part(s) of the geographic area under consideration is (are) safest for a single-family dwelling? A high-rise building? A government building? Commercial buildings? A school? A hospital? A dam? Short bridges? Long
- span bridges? Utility pipeline systems? A port?
- Which part(s) of the geographic area Is best for avoiding ground shaking above a certain threshold (such as 20 % of gravity, or 20 cm/sec, or 100 cm)? Soil amplification that enhances a particular period band of the ground motion (e.g., 0.2 second, 1.0 second, or 2.0 seconds)? Liquefaction? Lateral Spreads? Large volume landslides? Surface fault rupture? The "killer pulse" generated by the fling of the fault? Source directivity? Regional uplift or subsidence? Tsunami wave run up? Seich? Aftershocks?
- Which part(s) of the geographic area is(are) most vulnerable in a damaging earthquake? Which element(s) at risk is (are) most vulnerable?

<u>Acceleration</u>-Acceleration is a force having the units of gravity that denotes the rate of change of the back and forth movement of the ground during an earthquake. Velocity (the rate of the ground motion at a given instant of time with units of cm/s) and displacement (the distance the ground has moved from it's rest position with units of cm) are derived from an accelerogram.

Accelerogram-The record or time history obtained from an instrument called an accelerometer showing acceleration of a point on the ground or a point in a building as a function of time. The peak acceleration, the largest value of acceleration on the record is typically used in design criteria. The velocity and displacement time histories and the response spectrum are derived analytically from the time history of acceleration.

Active Fault-A fault is active if it exhibits physical characteristics such as historic earthquake activity, surface fault rupture, geologically recent displacement of stratigraphy or topography, or physical association with another fault system judged to be active. When these characteristics are suspected or proven, it is classed as active and judged to be able to undergo movement. See Fault.

Attenuation-A decrease in the strength of seismic waves and seismic energy with distance from the point where the fault rupture originated. Also referred to as Seismic Wave Attenuation Function.

Duration-A description of the length of time between the onset and the departure of a natural hazard. Also, a measure of the length of time the ground motion exceeds a given threshold of shaking, such as 5 % of the force of gravity.

Earthquake Hazards-The physical effects generated in an earthquake (e.g., ground shaking, ground failure, surface fault rupture, regional tectonic deformation, tsunami run up, seiches, and aftershocks).

Epicenter-The point on the earth's surface vertically above the point where the fault rupture originated.

Exceedance Probability-The probability (for example, 10 %) that an earthquake will generate a level of ground motion that exceeds a specified reference level during a given exposure time.

Exposure Time-The period of tine (for example, 50 years) that a structure or a community is exposed to potential earthquake ground shaking, ground failure, and other earthquake hazards

Fault-A fracture or a zone of fractures in the earth along which displacement of the two sides relative to one another has occurred as a consequence of compression, tension, or shearing stresses. A "blind fault" is the term used to describe a fault system that is not visible at the surface of the ground and can only be detected by using geophysical techniques such as drilling, seismic reflection profiles, gravity profiles, or magnetic profiles. A fault may rupture the ground surface during an earthquake, especially If the magnitude Is greater than M 5.5. The length of the fault is related to the maximum magnitude, with long faults able to generate larger-magnitude earthquakes than short faults. See Active Fault.

Focal Depth-The vertical distance between the point where the fault rupture originated and the earth's surface.

Ground failure-A-term referring to the permanent, Inelastic deformation of the soil and/or rock triggered by ground shaking. Landslides, the most common and wide spread type of ground failure, consists of falls, topples, slides, spreads, and flows of soil and/or rock on unstable slopes. Liquefaction, which results in a temporary loss of bearing strength, occurs mainly In young, shallow, loosely compacted, water saturated sand and gravel deposits when subjected to ground shaking. Surface fault rupture occurs in some earthquakes when the fault breaks the surface. Regional tectonic deformation, changes in elevation over regional distances, Is a feature of earthquakes having magnitudes of 8 or greater. Tsunami run up results when the long period ocean waves generated by the sudden, Impulsive, vertical displacement of a submarine earthquake, reaches low lying areas along the coast. Seiches are standing waves induced in lakes and harbors by earthquake ground shaking. Aftershocks refer to the long, exponentially decaying, sequence of smaller earthquakes that follow a largemagnitude earthquake for months to years, exacerbating the damage.

Ground shaking-This term refers to the dynamic, elastic, vibratory movement of the ground in response to the arrival and propagation of the elastic P, S, Love, and Rayleigh seismic waves. Ground shaking is characterized In terms of amplitude, frequency composition, duration, and energy, and is indicated in terms of Modified Mercalli Intensity , ground acceleration, ground velocity, ground displacement, and spectral response. Ground shaking can be Increased by soil amplification, source directivity, topography, anonomalously shallow focal depths, surface fault rupture, and the fling of the fault. The "killer pulse" is a long-duration acceleration pulse that is generated close to the causative fault and is thought to be related to the fling of the fault as It ruptures. All structures are vulnerable at some level of amplitude, frequency, and duration of ground shaking.

Hazard-A potential threat to humans and their welfare.

Hazard Assessment- An estimate of the range of the threat (i.e., magnitude, frequency, duration, areal extent, speed of onset spatial dispersion, and temporal spacing) to humans and their welfare from natural and technological hazards.

Intensity -A numerical index denoted by Roman numerals from I to XII describing the physical effects of an earthquake on the earth's surface, man, or on structures built by man. These values are determined subjectively by individuals performing post earthquake investigations to determine the nature and spatial extent of the damage distribution, not by Instrumental readings. The most commonly used scales throughout the word are Modified Mercalli Intensity (MMI), developed fn the 1930's by an Italian, and the MSK scale, developed in the 1960's by scientists in the former Soviet Union, which are essentially equivalent for intensities VII to X. Intensity VI denotes the threshold for potential ground failure such as liquefaction. Intensity VII denotes the threshold for architectural damage. Intensity VIII denotes the threshold for structural damage. Intensity IX denotes intense structural damage. Intensities X to XII denote various levels of total destruction. See Magnitude.

Magnitude-A numerical quantity, devised by the late Professor Charles F. Richter in the 1930's and denoted by Arabic integers with one decimal place accuracy (for example 7.8) to characterize earthquakes in terms of the total energy released after adjusting for difference in epicentral distance and focal depth. Magnitude differs from intensity in that magnitude is determined on the basis of instrumental records; whereas, intensity is determined on the basis of subjective observations of the damage. Measured on a logarithmic scale, magnitude Is open ended theoretically, with the largest earthquake to date being the M 9.5 Chile earthquake of 1960. Moderate-magnitude earthquakes have magnitudes between 5.5 and 7.0; large-magnitude earthquakes have magnitudes between 7.0 and 8.0; and great earthquakes have magnitudes of 8.0 and greater. The - energy Increases exponentially with magnitude. For example, a magnitude 6.0 earthquake releases 31.5

times more energy than a magnitude 5 earthquake, but (31.5) (31.5) or approximately 1,000 times more energy than a magnitude 4 : earthquake.

Natural Hazard -A potential threat to humans and their welfare caused by rapid and slow onset events having atmospheric, geologic, and hydrologic origins on solar, global, regional, national, and local scales (e.g., floods, severe storms, earthquakes, landslides, volcanic eruptions, wild fires, tsunamis, droughts, winter storms, coastal erosion, and space weather).

Response Spectrum-The response spectrum is a graph of the output of a mathematical model which shows how an idealized ensemble of lightly damped simple harmonic vibrating buildings respond to a particular ground motion accelerogram. The accelerogram Is used to excite them into vibration in the 0,05-10 seconds period range, the range of Interest to engineers. The concept of the response spectrum is used in building codes and the design of essential and critical structures.

Seismogenic Structure-A geologic structure such as an igneous pluton dike, or sill that has earthquake activity associated with it.

Soil Amplification-Soils have a period-dependent effect on the ground motion, increasing the level of shaking for certain periods of vibration and decreasing It for others as a function of the "softness" and thickness of the soil relative to the underlying rock and the three-dimensional properties of the soil/rock column.

Soil/Structure Resonance-A physical phenomenon Increasing the potential for destructiveness that results when the input seismic waves causes the underlying soil and the structure to resonate, or vibrate at the same period.

Source Directivity A phenomenon that increases ground shaking at a site. It results from the directional aspects of the fault rupture that cause most of the energy to be released in a particular direction instead of in all directions.

Surface Fault Rupture-A phenomenon that increases ground shaking at a site. Refers to the physical phenomenon of the rupturing fault breaking the surface of the ground, instead of stopping beneath the ground surface, and releasing more energy on the side of the fault that (s moving than on the stationary block.

Earthquake Resilient Buildings-Buildings that are sited, designed and constructed in such a way that they are able to resist the ground shaking from large magnitude earthquakes without collapsing and from moderate-magnitude earthquakes without significant loss of function and with damage that is repairable.

Elements at Risk-People, ecosystems, natural resources, the environment, buildings and infrastructure, essential facilities, and critical facilities that are voluntarily or involuntarily exposed to natural and technological hazards.

Infrastructure-These structures and facilities provide the essential functions of supply, disposal, communication, and transportation in a community. They are also called Community Lifelines

Risk-The probability of loss to the elements at risk as the result of the occurrence, physical and societal consequences of a natural or technological hazard, and the mitigation and preparedness measures in place In the community.

Risk Assessment-A risk assessment Is an objective scientific assessment of the chance of loss or adverse consequences when physical and social elements are exposed to potentially harmful natural and technological hazards. The endpoints or consequences depend on the hazard and include: damage, loss of economic value, loss of function, loss of natural resources, loss of ecological systems, environmental impact, deterioration of health, mortality, and morbidity. Risk assessments Integrate hazard assessments with the vulnerability of the exposed elements at risk to seek reliable answers to the following questions:

1. What can happen?

2. How likely are each of the possible outcomes?

3. When the possible outcomes happen, what are the likely consequences and losses?

Vulnerability-The potential loss in value of each element at risk from the occurrence and consequences of natural and technological hazards. The factors that influence vulnerability include: demographics, the age and resilience of the built environment, technology, social differentiation and diversity, regional and global economies, and political arrangements. Vulnerability is a result of flaws in planning, sitting, design, and construction.

Acceptable Risk-The probability of occurrences of physical, social, or economic consequences of an earthquake that is considered by authorities to be sufficiently low in comparison with the risks from other natural or technological hazards that these occurrences are accepted as realistic reference points for determining design requirements for structures, or for taking social, political, legal, and economic actions In the community to protect people and property. See Risk.

Disaster-hazardous event which adversely affects a community to such a degree that essential social structures and functions are disrupted. Disasters represent policy failures.

Public Policies-Public policies are designed to manage the potential risk from being exposed to one or more of the earthquake hazards. The policy options encompass: a) stop Increasing the risk to elements that will be exposed in the future to natural and technological hazards, and b) start decreasing the risk to existing elements already at risk from natural and technological hazards. They Include: Mitigation- A range of policies, legislative mandates, professional - practices, and social adjustments that are designed to reduce or minimize the effects of earthquakes and other natural hazards on a community. Mitigation measures implemented over the last 20 years have included: 1) land use planning and management, 2 engineering codes, standards and practices, 3) control and protection works, 4) prediction, forecasts, warning, and planning, 5) recovery, reconstruction, and planning, and 6) Insurance. Preparedness refers to a range of policies, legislative mandates, professional practices, and social adjustments that are used by Individuals, businesses, organizations, communities, and Nations to plan for emergency response, recovery, and reconstruction .after a damaging earthquake.

Risk Management-The public process of deciding what to do when risk assessments Indicate that risk, or the chance of loss, exists. Risk management encompasses choices and actions for communities and individuals (i.e., prevention, mitigation, preparedness which are designed to: a) stop increasing the risk to future elements that will be placed at risk to natural and technological hazards, b) start decreasing the risk to existing elements already at risk, and c) continue planning ways to respond to and recover from the inevitable natural and technological hazard, including the imponderable extreme situation or catastrophic event.

REFERENCES

Al-Zaid, R. (1988). Seismic Hazard Analysis and Specification of Ground Motion. Short course on " Earthquake Engineering ", Dept. of Civil Engineering, King Saud Univ.

Al-Zaid, R. (1988). Hazard Curves at Specific Sites and Zonation map of the Kingdom. Short course on " Earthquake Engineering ", Dept. of Civil Engineering, King Saud Univ.

Campbell, R.H., et al "Landslides Classification for Identification of Mud Flow and Other Landslide Hazards" and Keefer, P.K. "Landslides Caused by Earthquakes" in Proceedings of the Geologic and Hydrologic Training Program, Open File Report 84-760 (Reston, Virginia: U.S. Geological Survey, 1984).

Campbell, K.W., "Near Source Attenuation of Peak Horizontal Acceleration", Bulletin of the Seismological Society of America, Vol. 71, No. 6, 1981, pp. 20392070.

Gutenberg, B. And Richter, C.F. (1944)."Frequency of Earthquakes in California", Bulletin of the Seismological Society of America, Vol. 34, No. 4, pp. 1985-1988.

Hays, W.W., ed., 1981, Facing Geologic and Hydrologic Hazards -- Earth Science Considerations: U.S. Geological Survey Professional Paper 1240B, 108 p.

Kanamori, H. (1988)."Importance of Historical Seismograms for Geophysical Research", in W.H.K. Lee, H. Meyers, and K. Shimazaki, eds. Historical Seismograms and Earthquakes of the World, Academic Press, San Diego, California, pp. 16-31.

Lamarrae, M., and Shah, H.C., Seismic Hazard Evaluation for Sites in California: Development of an Expert System, The John A. Blume Earthquake Engineering Center, Report No. 85, Department of Civil Engineering, Stanford University, June 1988Reiter, L. (1990).Earthquake Hazard Analysis - Issues and Insights, Columbia University Press, New York, 254 pp.

Shah, H.C., Earthquake Engineering and Seismic Risk Analysis. Lecture Notes, The John A. Blume Earthquake Engineering Center. Department of Civil Engineering, Stanford University.

Smith, S.W. (1976)."Determination of Maximum Earthquake Magnitude", Geophysical Research Letters, Vol. 3, No. 6, pp. 351-354.

Stanford Seismic Hazard Analysis (STASHA), Computer Program, The John A. Blume Earthquake Engineering Center, Technical Report No. 36, Stanford University, 1989.

Thenhaus, P.C., Algermission, ST., Perkins, D.M., Hanson, S.L., and Diment, W.H., "Probabilistic Estimates of Seismic Ground Motion Hazard in the Western of Saudi Arabia", Kingdom of Saudi Arabia, U.S. Geological Survey Open File Report No. OF-06-O8, 1986.