Process of Seismic Hazards

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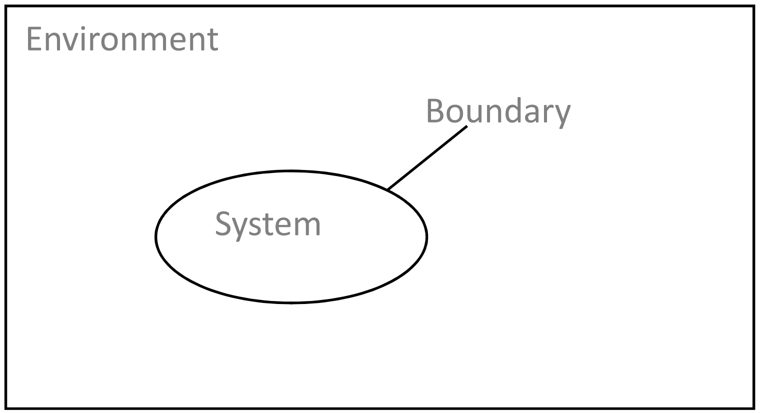
Definition of System



System is a set of interacting or interdependent entities, real or abstract, forming an integrated whole.

Definition of System

A **system** is a fundamental concept of systems theory, a way of thinking about the world, a model. We determine a system by choosing the relevant interactions we want to consider, plus choosing the **system boundary** —– or, equivalently, providing membership criteria to determine which entities are part of the system, and which entities are outside of the system and are therefore part of the **environment** of the system.

There are natural and man-made (designed) systems. Man-made systems normally have a certain purpose, objectives. They are “designed to work as a coherent entity”. Natural systems may not have an apparent objective.

An open system usually interacts with some entities in their environment. A closed system is isolated from its environment.

Earth's Crust System

The earth's crust, which has seismic sources in itself, makes earthquakes and the potentially damaging phenomena associated with earthquakes, such as ground shaking, liquefaction, landslides, and tsunami, and influences and changes the environment of human living and nature, should be considered as a natural, open, complicated system.

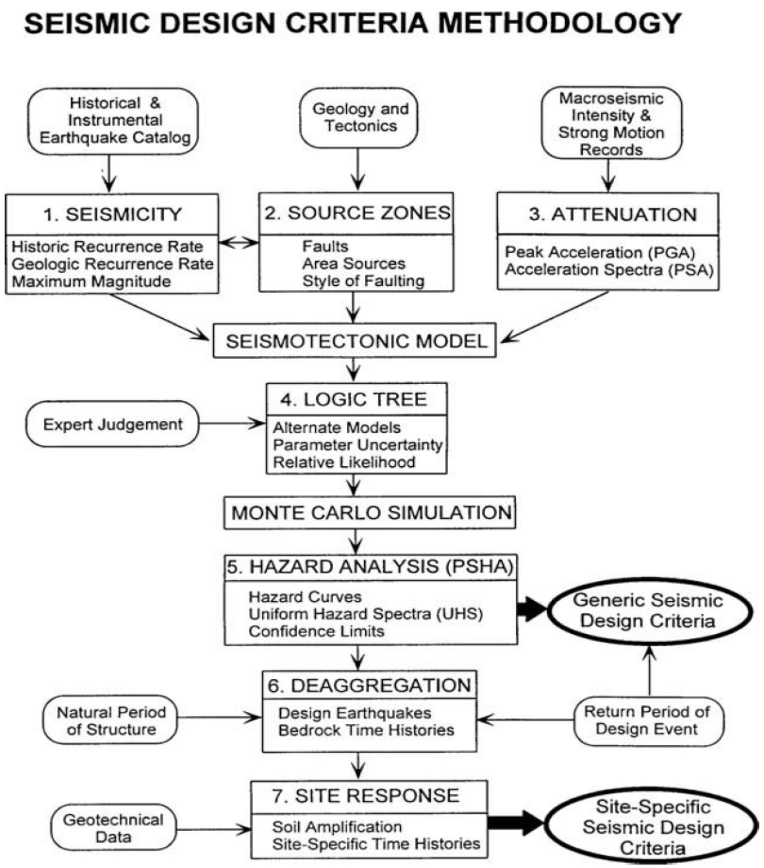
What we are going to do, is to study this system and **try to forecast the earth's surface motion at sites of engineering interest.**

Probabilistic Seismic Hazard Methodology

Probabilistic seismic hazard analysis (PSHA) for assessing earthquake hazards has a widespread use in recent years.

In principle, PSHA can address any natural hazard associated with earthquakes, including ground shaking, fault rupture, landslide, liquefaction, seiche, or tsunami. However, most interest is in the probabilistic estimation of ground-shaking hazard, since it causes the largest economic losses in most earthquakes. The presentation here is restricted to the estimation of the earthquake ground motion hazard.

Probabilistic Seismic Hazard Methodology



Probabilistic Seismic Hazard Methodology

PSHA can be summarized as the solution of the following expression of the total probability theorem:

$$\lambda\left[X \geq x\right] \approx \sum_{Sources\ i} \nu_i \int_{M_o}^{M_{Max}} \int_{R|M} P\left[X \geq x \middle| M, R\right] f_M(m)\, f_{R|M}(r|m)\, dr\, dm$$

where $\lambda[X \geq x]$ is the annual frequency that ground motion at a site exceeds the chosen level $X = x$; ν_i is the annual rate of occurrence of earthquakes on seismic source i, having magnitudes between M_o and M_{Max}; M_o is the minimum magnitude of engineering significance; M_{Max} is the maximum magnitude assumed to occur on the source; $P[X \geq x|M,R]$ denotes the conditional probability that the chosen ground motion level is exceeded for a given magnitude and distance; $f_M(\text{m})$ is the probability density function of earthquake magnitude; $f_{R|M}(r|m)$ is the probability density function of distance from the earthquake source to the site of interest. In application, this expression is solved for each seismic source i of a seismotectonic model.

Probabilistic Seismic Hazard Methodology

Once the annual exceedance rate λ[X ≥ x] is known, the probability that an observed ground motion parameter X will be greater than or equal to the value x in the next t years (the exposure period) is easily computed from the equation:

$$P\left[X \geq x\right] = 1 - \exp\left(-t\lambda\left[X \geq x\right]\right)$$

where the "return period" of x is defined as:

$$R_X\left(x\right) = \frac{1}{\lambda\left[X \geq x\right]} = \frac{-t}{\ln\left(1 - P\left[X \geq x\right]\right)}$$

Probabilistic Seismic Hazard Methodology

Probability values commonly used and cited in PSHA are ground motions that have a 10% probability of being exceeded in a 50-year exposure period of engineering interest. From Equation 8.3, this gives a return period of:

$$R_X(x) = \frac{-50}{\ln(1-0.1)} = 475 \text{ years}$$

Constituent Models of the Probabilistic Seismic Hazard Methodology

The constituent models of the probabilistic approach to estimating earthquake ground motion hazard are:

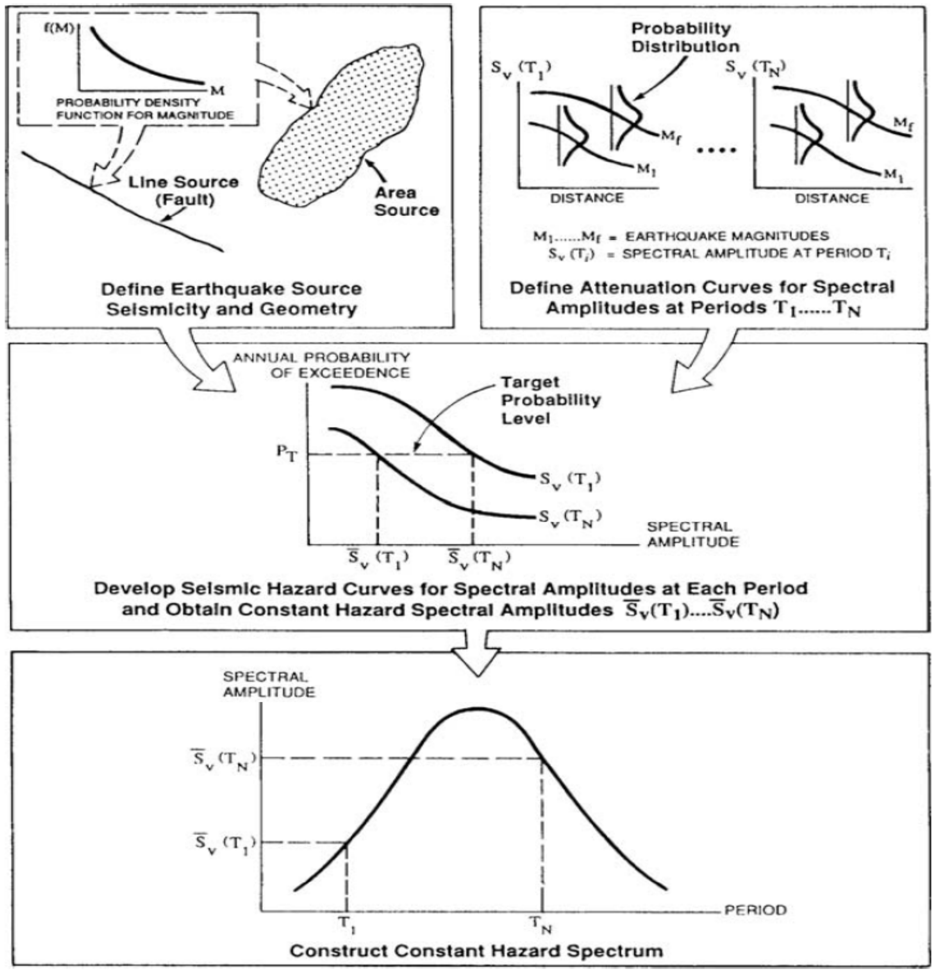
1. Seismic sources

2. Earthquake recurrence frequency

3. Ground motion attenuation

4. Ground motion occurrence probability at a site

Constituent Models of the Probabilistic Seismic Hazard Methodology



Definition of Seismic Sources

The fundamental assumptions of a defined earthquake source is

1. earthquake occurrence is uniformly distributed for given magnitude within the source

2. earthquake occurrence is only considered between a minimum earthquake magnitude of engineering interest (M_{min}) and a maximum magnitude (M_{max}) that is representative of the entire source

Definition of Seismic Sources

2 kinds of earthquake sources: Area Sources & Fault Sources

Area seismic sources define regions of the Earth's crust that are assumed to have uniform seismicity characteristics that are distinct from neighboring zones.

Line sources are defined in PSHA ground motion analyses as map-view representations of three-dimensional fault planes for the purpose of explicit representation of faults that are considered capable of earthquake rupture.

Earthquake Frequency Assessments

There are two fundamental approaches to assess earthquake recurrence frequency of the defined seismic sources in PSHA. These are **historical** and **geological** frequency assessments.

Historical frequency assessments are based on statistical analyses of the historical catalog of earthquakes that have occurred within a region.

Geological frequency assessments are generally based either on a prehistoric record of earthquake occurrence on faults (termed paleoseismicity), which is compiled through detailed field geologic investigations, or on physical estimates of seismic moment either on individual faults or distributed throughout broad regions.

Earthquake Frequency Assessments

For historical frequency assessments, most commonly, the statistical procedures proposed by Stepp [1972] are used to assess completeness times of the reported magnitudes, which assume the earthquake sequence in a catalog can be modeled as a Poisson distribution. If k1, k2, k3… kn are the number of events per unit time interval, then:

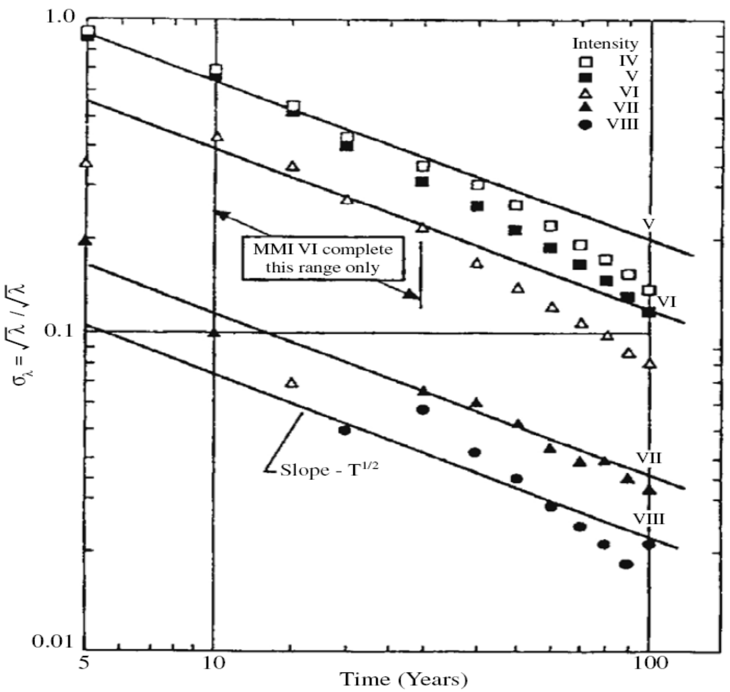
$$\lambda = \frac{1}{n}\sum_{i=1}^{n} k_i$$

and its variance is $\sigma^2 = \lambda/n$, where n equals the number of unit time intervals. If unit time is one year, $\sigma_\lambda = \lambda^{1/2}/T^{1/2}$ as the standard deviation of the estimate of the mean where T is the sample length in years.

Earthquake Frequency Assessments

If data for a magnitude interval are plotted as log (σ_λ) vs. log (T), then the portion of the line with slope $T^{-1/2}$ can be considered homogeneous and used with data for other magnitude ranges (but for different observational periods) similarly tested for homogeneity to develop estimates of recurrence frequency.

Earthquake Frequency Assessments



Completeness time plots in terms of earthquake epicenter intensity following the method of Stepp[1973]. Each symbol refers to a different earthquake intensity class.

Earthquake Frequency Assessments

Over large regions, Gutenberg and Richter [1954] found that the average recurrence frequency of earthquakes follows an exponential distribution related to magnitude:

$$\log N(m) = a - bm$$

where N(m) = the number of earthquake events equal to or greater than magnitude m occurring on a seismic source per unit time, and a and b are regional constants (10^a = the total number of earthquakes with magnitude > 0, and b is the rate of seismicity; b is typically 1 ± 0.3).

Earthquake Frequency Assessments

In its cumulative form, the Gutenberg–Richter relation of recurrence frequencies is unbounded at the upper magnitude. In PSHA, this relationship imposes the unrealistic assumption that the maximum potential earthquake for any region under consideration is unbounded and unrelated to the seismotectonic setting. The truncated exponential recurrence relationship [Cornell and Vanmarcke, 1969] is therefore commonly used in practice:

$$N(m) = N(m^0)\,\frac{\exp\left(-\beta\left(m-m^0\right)\right)-\exp\left(-\beta\left(m^u-m^0\right)\right)}{1-\exp\left(-\beta\left(m^u-m^0\right)\right)} \quad \text{for} \quad m \leq m^u$$

where m^0 is an arbitrary reference magnitude; m^u is an upper-bound magnitude where $N(m) = 0$ for $m > m^u$; and $\beta = b \cdot \ln 10$. In this form, earthquake frequency approaches zero for some chosen maximum earthquake of a region.

Earthquake Frequency Assessments

For geologic earthquake frequency assessments, Characterizing earthquake recurrence frequency on individual faults, as opposed to regionally distributed area sources, is a more challenging proposition.

Fault slip-rate can be related to earthquake occurrence frequency through the use of seismic moment [Molnar, 1979; Anderson, 1979]. Seismic moment, M_o , is the most physically meaningful way to describe the size of an earthquake in terms of static fault parameters. It is defined as:

$$M_o = \mu A_f D$$

where μ is the rigidity or shear modulus of the fault, usually taken to be 3 × 10^{11} dyne/cm^2; A_f is the rupture area on the fault plane undergoing slip during the earthquake; and D is the average displacement over the slip surface.

Earthquake Frequency Assessments

The seismic moment is translated to earthquake magnitude according to an expression of the form:

$$M_W = \frac{2}{3}\log_{10} M_0 - 6$$

Where M_w is the magnitude.

Earthquake Frequency Assessments

According to Brune [1968], the slip rate of a fault can be related to the seismic moment rate M_0^T as follows:

$$M_o^T = \mu A_f S$$

where S is the average slip rate (per unit time) along the fault.

The seismic moment rate, therefore, provides an important link between geologic and seismicity data.

Earthquake Frequency Assessments

Surface-rupturing earthquakes tend to occur within a relatively narrow range of magnitudes at an increased frequency. They have been termed **characteristic earthquakes.** The characteristic recurrence frequency distribution reconciles the exponential rate of small- and moderate-magnitude earthquakes with the larger characteristic earthquakes on individual faults.

Earthquake Frequency Assessments

The characteristic recurrence frequency distribution can be separated into a noncharacteristic Gutenberg–Richter relationship for small and moderate earthquakes, and a characteristic frequency part for large earthquake occurrence. The cumulative rate of noncharacteristic, exponentially distributed earthquakes, N_e, is estimated from the seismic moment and seismic moment rate as follows:

$$N_e = M_o^T \frac{1 - e^{-\beta(m_u - 0.25)}}{M_o e^{-\beta(m_u - 0.25)} \left(\frac{b10^{-c/2}}{c-b} + \frac{b10^{b}\left(1 - 10^{-c/2}\right)}{c} \right)}$$

Earthquake Frequency Assessments

The cumulative rate of characteristic earthquakes, N_c, is related to the cumulative rate of noncharacteristic earthquakes by the expression:

$$N_c = \frac{\beta N_e e^{-\beta(m_u - m_0 - 1.5)}}{2\left(1 - e^{-\beta(m_u - m_0 - 0.5)}\right)}$$

Maximum Magnitude Assessments

Assessment of the maximum magnitude earthquake for the defined seismic sources is an important, fundamental task in PSHA. It is sorted by the different types of the earthquake sources. Both of them can be calculated basing on historical earthquakes statistics, or alternative data from a similar region, or measurement from the earthquake waves.

Ground Motion Attenuation Relationships

Ground motion attenuation relationshipsis a particularly important element in PSHA for three reasons:

1. It dictates the detailed requirements of the seismic source definition.

2. It dictates the ground motion parameters that may be estimated.

3. It is a major contributor to uncertainty in the PSHA results .

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Ground Motion Attenuation Relationships

Most modern attenuation relationships for active tectonic regions are based on various distance measures from the fault rupture zone. These relationships allow the specification of the top and bottom of seismogenic faulting (as in the seismogenic layer), can accommodate specific definitions of fault-dip (i.e., the inclination of the fault from horizontal), and require specification of the style of faulting for each defined source.

In addition to defining the earthquake source, application of ground motion attenuation relationships is specific to a soil or rock type on which the PSHA ground motion estimate is to be made. These ground types are referred to as the site class, and are defined in broad categories such as hard rock, soft rock, firm soil, and soft soil.

Typical Engineering Products of PSHA

The fundamental engineering product of PSHA is an amplitude of some ground motion parameter that is associated with a particular return period.

Probabilistic results can be presented in a number of formats. Perhaps the most widely recognized product is that of a ground motion hazard map. Such maps illustrate the regional differences in ground motion amplitude (typically peak ground acceleration, or PGA) at a constant return period (i.e., a constant probability of exceedance).

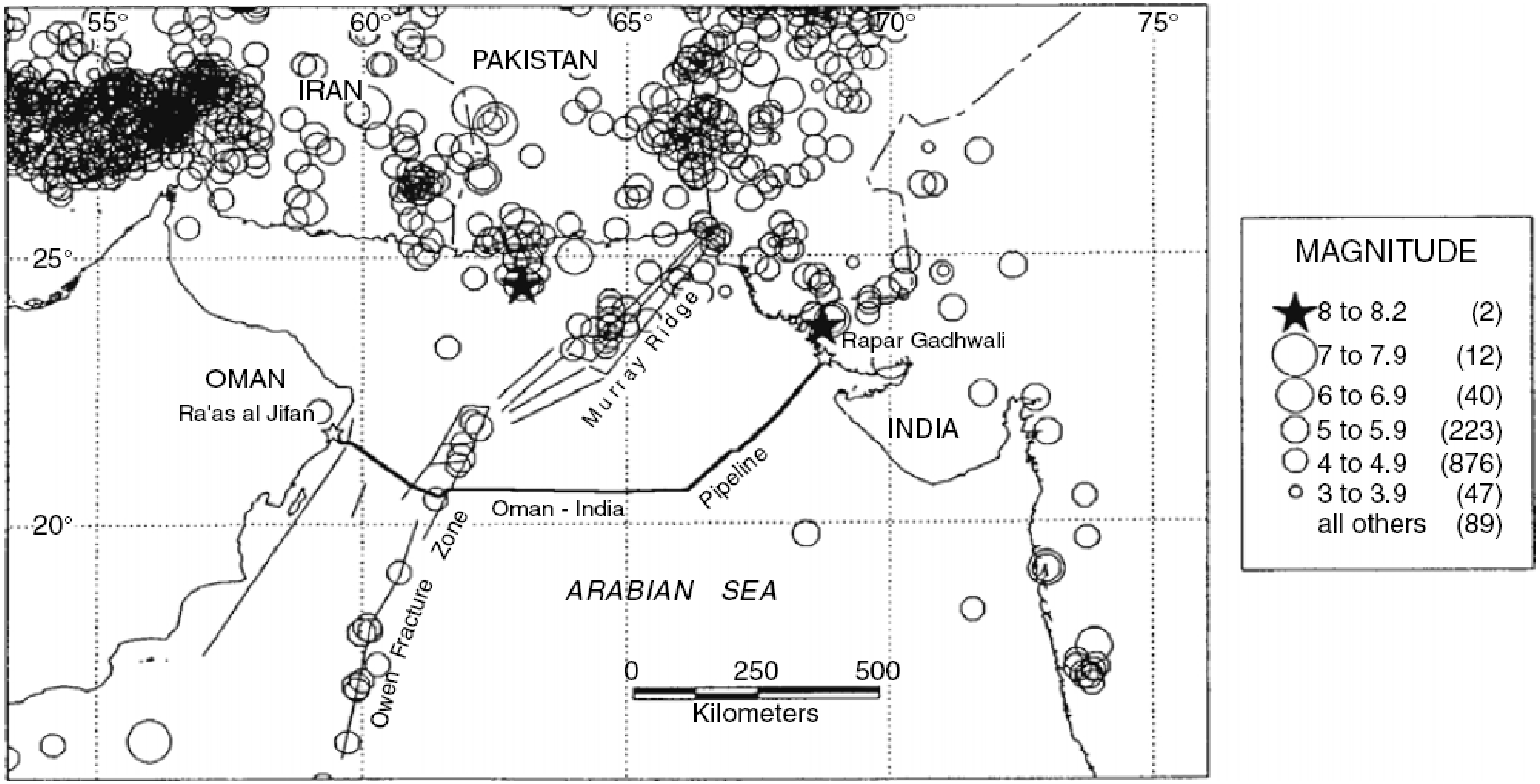
A common goal of hazard models is to rapidly estimate a hazard curve for a particular engineering site of interest. The hazard curve is a plot showing the change in ground motion amplitude relative to return period.

Another common product in engineering PSHA is the constant-probability, or uniform hazard, response spectrum.

PSHA Case Study

This section presents an illustrative case study of a simple, median, peak ground acceleration (PGA) hazard assessment along the proposed offshore Oman India pipeline route. The proposed Oman India pipeline traverses approximately 1135 km of the northern Arabian Sea floor and adjacent continental shelves at water depths of over 3 km on its route from Ra’s al Jifan, Oman, to Rapar Gadhwali, India (Figure 8.20). Ground-shaking hazard was quantified in terms of PGA for return periods of 200, 500, and 1000 years using the PSHA computer program Seisrisk III [Bender and Perkins, 1987].

PSHA Case Study



Location map of the Oman India pipeline route shown in relation to the regional distribution of earthquakes.

PSHA Case Study

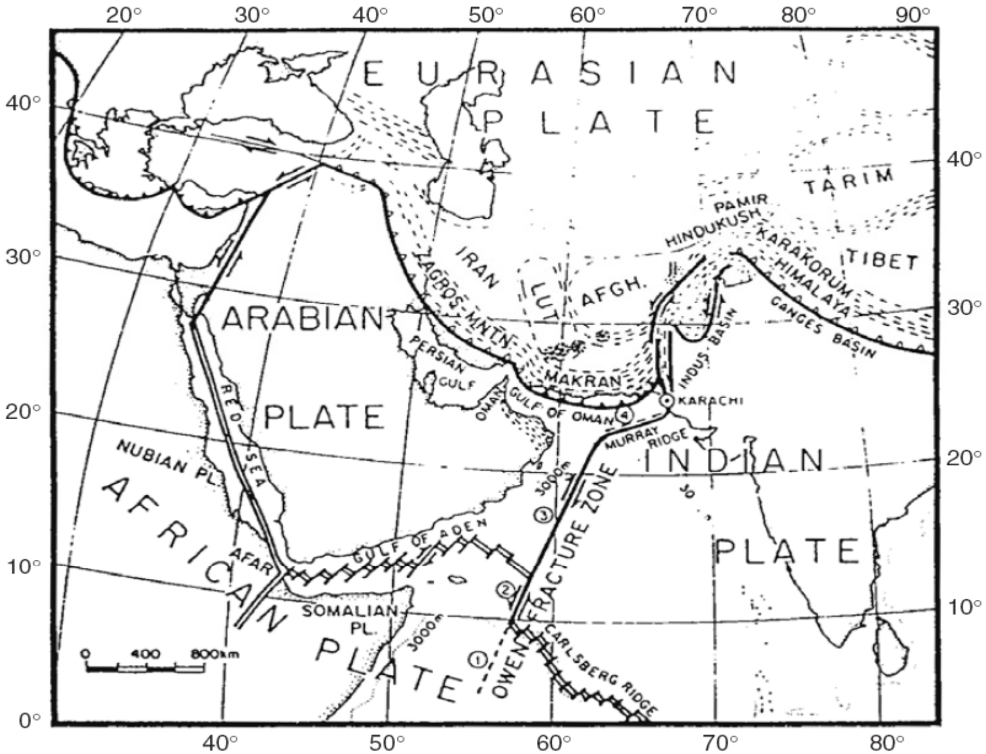


Plate tectonic setting of the region surrounding the northern Arabian Sea
showing regional tectonic
features.

PSHA Case Study

Earthquake Source Characterization-Makran Subduction Zone

The largest known earthquake on the Makran Subduction Zone was an M_S 8.2 earthquake in 1945. However, there is no reason to believe that the entire plate interface cannot rupture in a single “megathrust” earthquake. Based on this hypothesis, we assigned a maximum magnitude of 9.2 to this zone, consistent with both empirical rupture area–magnitude relationships and the magnitude of the great 1964 Prince William Sound, Alaska earthquake that ruptured a similar length.

PSHA Case Study

Earthquake Source Characterization-Makran Subduction Zone

We adopted area-normalized earthquake recurrence rates that were developed from the historical occurrence of earthquakes in this zone [Khattri et al., 1984]. These rates, which were defined in M_S, were adjusted to correspond to M_W using common empirical relationships between these two magnitudes' measures. Khattri et al.'s [1984] recurrence frequencies were normalized to a 40-year time period, not the 1-year time period that is usually used to develop earthquake recurrence relationships. For consistency with other recurrence relationships developed in this study, we converted these rates to an annual rate.

We partitioned these recurrence frequencies into two parts. Earthquakes of $7.6 \leq M \leq 9.2$ were assumed to occur on the plate interface. Earthquakes of $M < 7.6$ were assumed to occur within the shallow crust of the overriding Eurasian plate.

PSHA Case Study

Ground Motion Models

PGA was estimated from attenuation relationships of the form:

$$\log(\mathrm{PGA}) = b_1 + b_2\mathrm{M} - b_3\log R - b_4 R + \varepsilon$$

where PGA is the mean horizontal component of peak ground acceleration (g), M is earthquake magnitude (M_W), R is distance from the earthquake source to the site (km), ε is a random error term with a mean of zero and a standard deviation equal to the standard error of estimate of log (PGA), and b_1 through b_4 are parameters dependent on the tectonic environment.

PSHA Case Study

Soil Amplification Factors

The soil amplification factors for each of the soil classifications given by Borcherdt [1993] were normalized to hard rock and the amplitude of PGA for the existing soil conditions are obtained by multiplying the estimate of PGA on hard rock by these normalized factors. The maximum value of PGA on soft soils was limited to 0.45 g based on site-response studies of Holocene Bay Mud in the San Francisco Bay area. If shear strains large enough to cause significant cyclic degradation (e.g., liquefaction) are induced in these deposits, then actual values of PGA for these soft soils may be further limited to values on the order of 0.2 to 0.25 g. Of course, for such large strains, ground failure will become an important issue.

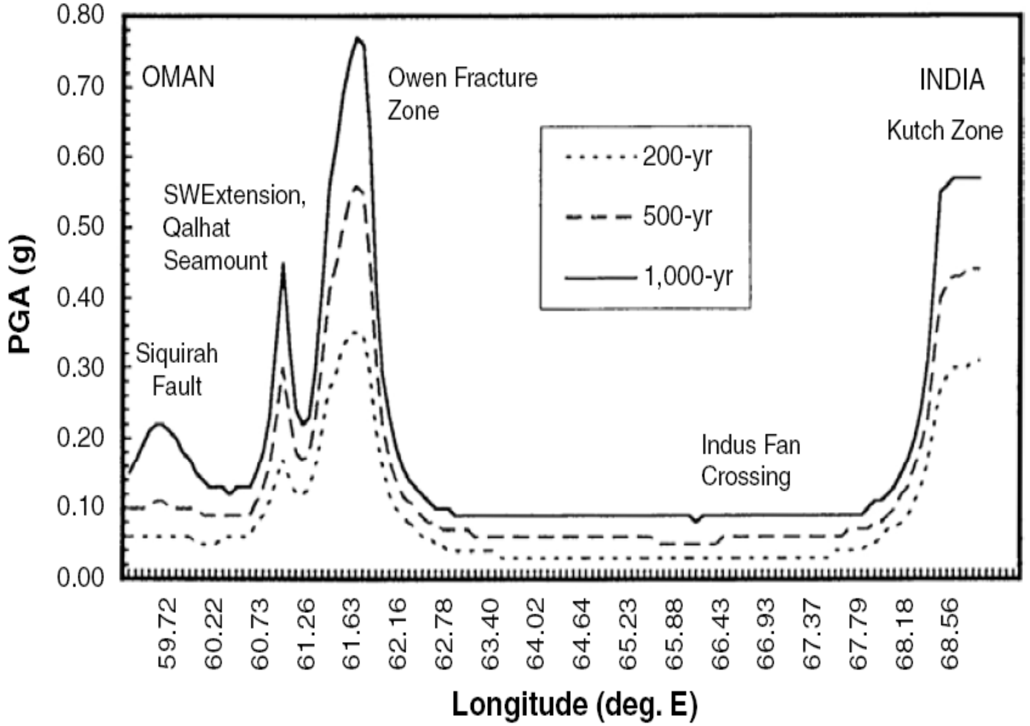
PSHA Case Study

Results

Values of PGA on hard rock were calculated at 130 locations along the pipeline route for return periods of 200, 500, and 1000 years. A map showing 500-year values of PGA on hard rock and on the existing soil conditions at mudline (in parentheses) at selected locations along the pipeline route and Indus Canyon is given in next figure. The existing soil conditions at all of the selected sites were classified as soft soil.

PSHA Case Study

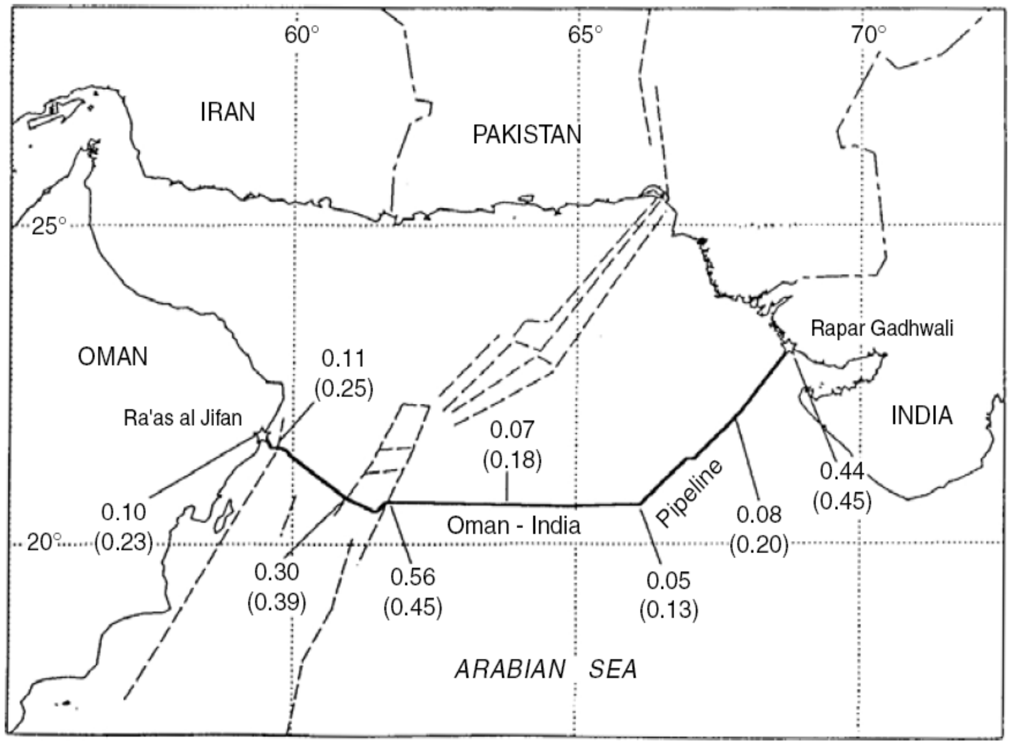
Results



Longitudinal profile of PGA on hard rock along the pipeline route for three return periods.

PSHA Case Study

Results



Calculated PGA on hard rock and soft soil (in parentheses) with a return period of 500 years at selected locations along the pipeline route and at the Indus Canyon.

PSHA Case Study

Conclusions

The computed ground-shaking hazard along the Oman India pipeline was found to be relatively high in the vicinity of the Owen Fracture Zone–Murray Ridge Complex and at the India coast in the Kutch region. These values are high enough to potentially trigger geologic hazards such as liquefaction, slope instability, and turbidity flows in areas that are susceptible to these hazards. Although the computed ground-shaking hazard elsewhere along the pipeline route was found to be relatively low, estimates of PGA are high enough offshore to also potentially trigger geologic hazards in areas that are highly susceptible to these hazards (e.g., unstable channel slopes).

End

Thank you!