Seismic Hazard Analysis

for the cities of

Islamabad and Rawalpindi

by

NORSAR

and

Pakistan Meteorological Department

February, 2006

Preface

The devastating 8th October 2005 earthquake necessitated the need for redefining the seismic zoning and updating the building codes in the country. Ministry of Housing & Works has recently undertaken its preliminary task of redefining Islamabad seismic zoning. Our study would help in reconfirming the results obtained by Ministry of Housing & Works.

The present study is a result of a short cooperation project between NORSAR, Norway and Pakistan Meteorological Department (PMD), Pakistan. The funding for this study was facilitated by the Norwegian Ministry of Foreign Affairs through the Norwegian Embassy, and the Government of Pakistan through the bilateral framework for institutional cooperation, which is coordinated by the Planning & Development Division out of the Pak-3004 Institutional Cooperation Programme.

The current work is the first phase for providing ground shaking information as basis for the new building code, and the present report was largely conducted during a two week visit of Dr. Conrad Lindholm from NORSAR to PMD, in which also initial training of Probabilistic Seismic Hazard Analysis (PSHA) was incorporated. The study presented herein is a preliminary investigation. It is intended to be followed by update studies and similar investigations for adjacent regions.

During the study, besides field visits, extensive discussions were undertaken with relevant experts. From PMD, the experts who participated in the study include Mr. Zahid Rafi, Mr. Ameer Haider, Mr. Sajjad Ahmad and Mr. Afsar Khan and from NORSAR, Dr. Conrad Lindholm headed this study.

Pakistan Meteorological Department
Islamabad
February 8, 2006

Dr. Qamar-uz-Zaman Chaudhry
Director General

Table of Contents

Executive Summary

The earthquake hazard has been computed for the cities of Islamabad and Rawalpindi using the probabilistic methodologies combined with semi-deterministic fault modeling. The results within the area considered vary insignificantly for bedrock ground motion levels. Due to varying soil thickness and soil consistency the ground shaking may be differentiated over the areas covered, however, a detailed microzonation work (which is outside the scope of the present study) is required to delineate the geographical distribution of soil amplification.

The results are provided in terms of Peak Ground Accelerations (PGA) for various annual exceedence probabilities. The hazard curve for hard rock is provided in Figure 1 and is tabulated in Table 1, indicating that for a return period of 500 years (0.002 annual exceedance probability) the expected ground motion at hard rock sites is 1.9 m/ss corresponding to 0.19 g. The results for hard rock conditions are shown in Fig. 1 and Table 1.

A preliminary soil amplification factor was computed for one typical soil site in the area, indicating a PGA amplification factor of 1.5.

These results can be used as anchoring points for horizontal elastic response spectra, where UBC or other codes may be used for defining the spectral shape which will also depend on local soil conditions.

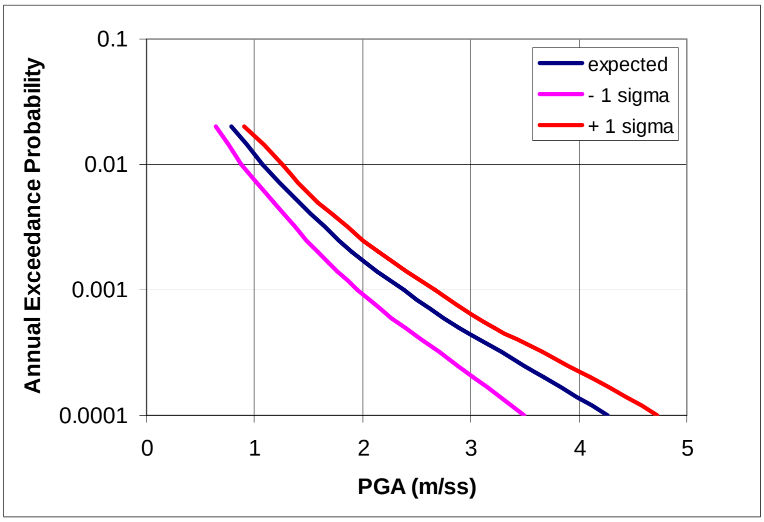


Fig. 1. Seismic hazard curve for the site 73.03E and 33.62N.

Annual Exceedence probability	Return period (years)	Expected value	Expected -1 σ	Expected +1σ
0.02	50	0.78611	0.64651	0.90545
0.01	100	1.07741	0.87129	1.25299
0.005	200	1.41609	1.17422	1.58578
0.002	500	1.90122	1.58423	2.14718
0.001	1000	2.37584	1.94753	2.67377
0.0005	2000	2.88964	2.39413	3.22235
0.0002	5000	3.67634	3.02297	4.10516

Table 1. Ground motion values (PGA in m/ss) for different annual exceedence probabilities for the site 73.03E and 33.62N. The light shaded row corresponds to the annual exceedance probability most frequently used. The shaded column is the expected ground motion.

1. Introduction

Over the last 100 years Pakistan has experienced several damaging earthquakes, but only three that must be characterized as national disasters, the Quetta earthquake in 1935, the Makran coast earthquake with tsunami generation in 1945 and the latest Muzafarrabad earthquake on the 8'th October 2005.

The last earthquake enhanced the consciousness about the increasing vulnerability the growing population is confronted with, as more and more people are concentrated in smaller and larger cities, and frequently in buildings with poor seismic resistance capacities. While earth scientists for some time have warned for future possible disastrous earthquakes in the Himalayas (e.g. Bilham et al., 2001), this has not been (sufficiently) recognized by the civil authorities.

On the global level it is more and more realized that poor constructions are the main reason for the high number of victims in any earthquake disaster, and a reevaluation of the National Building code of Pakistan has been scheduled, starting with the cities of Islamabad and Rawalpindi.

The present report is part of the building code update initiative.

2. Technical Approach

2.1. Principles of earthquake resistant design

While the present study is entirely focused on the probabilistic computation of ground shaking at various probability exceedence levels we have found it appropriate to initiate this report with a short resume of commonly used terms and principles in earthquake resistant design.

The antiseismic regulations provide different forms of quantification to reach the qualitative goal of safe design. The Eurocode 8 defines two goals of the antiseismic design:

- The no collapse requirement:
  - The structure shall be designed to withstand the design seismic action (load) without local or general collapse.
- The damage limitation requirement:
  - The structure shall be designed and constructed to withstand a seismic action (load) having a larger probability of occurrence than the design seismic action.

The above requirement are often also represented in the ULS and SLS definitions.

- ULS - Ultimate Limit States, are those associated with collapse or with other forms of structural failure which may endanger the safety of people or cause substantial environmental pollution.
- SLS - Serviceability Limit States, are those associated with damage occurrence, corresponding to states beyond which specified service requirements are no longer met.

The objective of the present report is to provide the seismic loads (seismic actions) at various annual exceedance probabilities. The contractor must choose an appropriate risk level (exceedance probability level) for the structure to which the design ground motion is associated.

The selection of the appropriate risk level is essentially a question of the consequences of a failure. The risk level is most often specified either as annual exceedance probability or in exceedance probability during the expected lifetime of the structure. The discussion of risk levels is supported through the following connection between return period T_R and life time T, where P is annual probability of exceedance:

$$T_R = \frac{-T}{\ln(1 - P(Z > z))}$$

If for example the expected lifetime of a structure is T=200 years, and a 95% non-exceedance probability (5% exceedance probability, P=0.05) is required, then this safety requirement corresponds to a return period of T_R =3900 years, or an equivalent $3*10^{-4}$ annual exceedance probability. The curves for various lifetime structures and the corresponding return periods are shown below in Fig. 2.1.

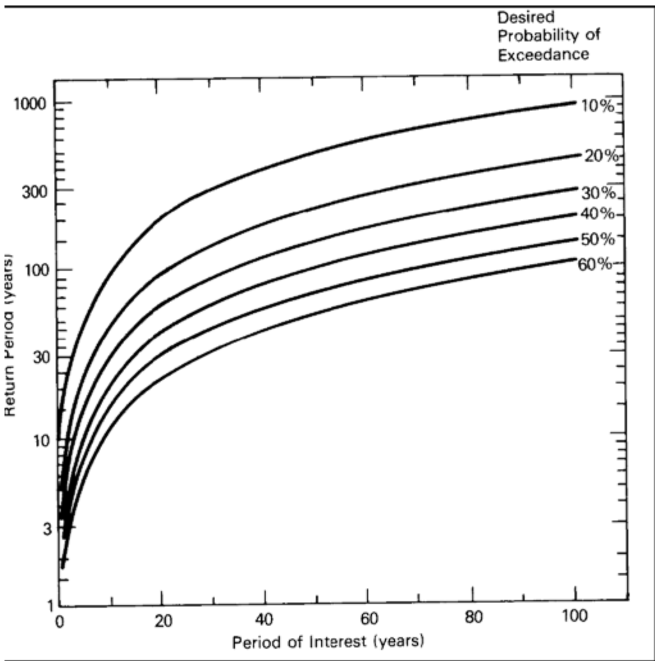


Figure 2.1. Relationship between return period (inverse of annual exceedance probability), period of interest and desired probability of exceedance during the period of interest. From Reiter (1990).

The U.S. Army Corps of Engineers have issued a manual under Engineering and Design (U.S. Army Corps of Engineers, 1999) in which several general guidelines are included. While their approach is generally deterministic there are key concepts that are applicable also to the present study. The seismic assessment has several key steps:

- Establishment of the earthquake design criteria. In the present case this means that the definitions of Maximum Design Earthquake (MDE) and Operating Basis Earthquake (OBE) are commonly understood.
- Development of ground motion corresponding to the MDE and OBE levels.
- Establishment of analysis procedures, i.e. procedures applied to reveal how the structure responds to the specified.
- Development of structural models.
- Prediction of earthquake response of the structure.

- Interpretation and evaluation of the results.

For the present study we will exclusively focus on point 2 above, except that we refrain from using the terms MDE or OBE in the following, since these terms are relevant in particular for sensitive structures. The background is however a clear understanding of the MDE and OBE definitions:

- The Operating Basis Earthquake (OBE) is an earthquake or equivalent ground motion that can reasonably be expected to occur within the service life of the project, that is, with a 50% probability of exceedance during the service life. The associated performance requirement is that the project functions with little or no damage, and without interruption of function.
- The Maximum Design Earthquake (MDE) is the maximum earthquake or equivalent level of ground motion for which the structure is designed or evaluated. The associated performance requirement is that the project performs without catastrophic failure although severe damage or loss may be tolerated.

While we in the following provide ground motions for different annual exceedance probabilities, it is the responsibility of any contractor to associate the safety levels in terms of MDE and OBE or in accordance with national building regulations.

2.2. PSHA; Methodological approach

2.3. General

The foundations of probabilistic engineering seismic hazard analyses were established by Cornell (1968), who recognized the need for seismic hazard to be based on a method which properly accounted for the intrinsic uncertainties associated with earthquake phenomena. Since then, both seismological and geological techniques and understanding applied to seismic hazard analysis have improved steadily, so that current practice is now able to utilize information from a variety of both seismological and geological data sources with due considerations for uncertainties. Significant improvements have also been achieved over the last 20 years on the modeling side.

One of the most important of these improvements has been in seismic source modeling. Originally, seismic sources were crudely represented as area zones which could be narrowed to represent the surface outcrop of faults as in McGuire's (1976) computer program EQRISK. An improved scheme, which included the effects of fault rupture, was proposed by Der Kiureghian and Ang (1977), and in a modified form implemented by McGuire (1978) in his fault modeling program FRISK, written as a supplement to his earlier and very popular EQRISK area source program.

While the standard practice for a long time was to present the results of seismic hazard analyses in terms of a single best estimate hazard curve, the growing awareness of the importance of parametric variability and the trend to consult expert opinion in matters of scientific doubt, led later to the formulation of Bayesian models of hazard analysis (Mortgat and Shah, 1979) which seek to quantify uncertainty in parameter assignment in probabilistic terms. This approach has been formalized into a logic tree methodology (Kulkarni et al., 1984; Youngs and Coppersmith, 1985), which represents the range of possible parameter values as branches of a computational tree which are individually weighted and whose contributions to seismic hazard are separately evaluated and statistically combined.

To meet the need for a state-of-the-art computer program capable of detailed hazard modeling, for areas with seismic activity ranging from low to high, a program PRISK was developed (Woo, 1985), which has later been developed and modified into the herein used NPRISK computer code. The program took as a starting point the two McGuire area source and fault modeling programs EQRISK and FRISK, but with extensive restructuring and extensions to implement an efficient logic tree formalism covering the modeling of area zones and three dimensional faults with first order curvatures both in strike and dip directions.

A flow chart describing the various steps involved in our probabilistic computation of seismic hazard at bedrock outcrop level is given in Fig. 2.2 and Fig. 2.3, and the logic tree formalism used in the hazard analysis is explained in Fig. 2.4.

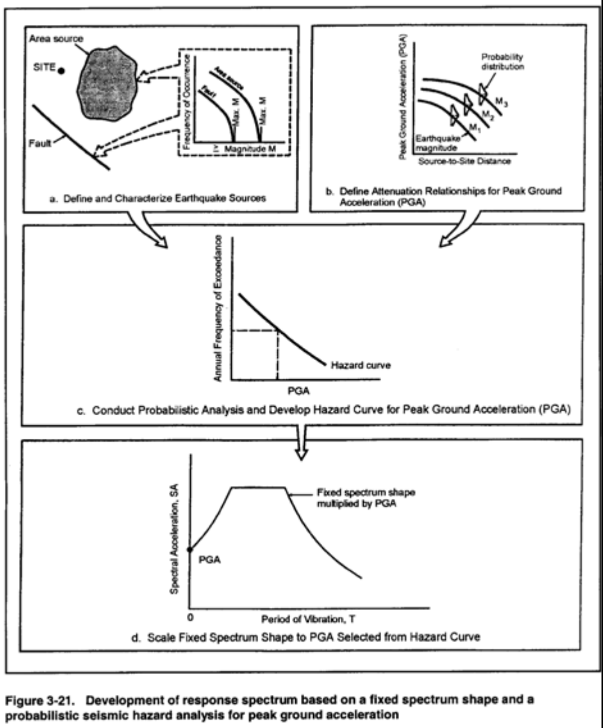


Fig. 2.2. Simple layout of probabilistic earthquake ground motion (GM) hazard computation, and the associated response spectrum with fixed shape.

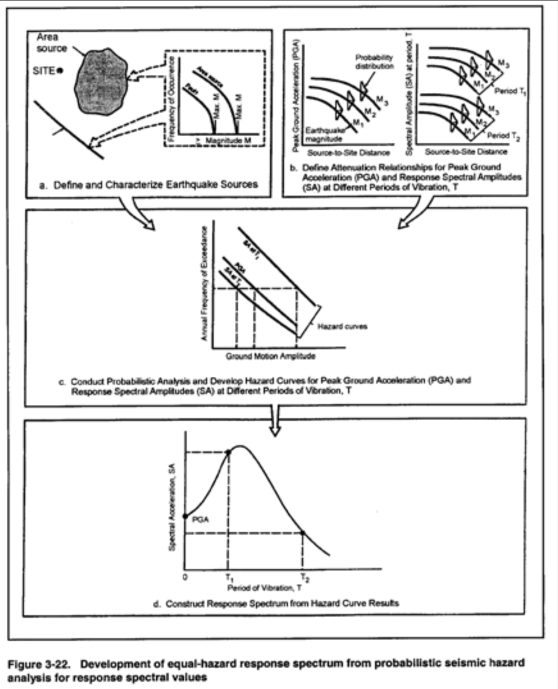


Fig. 2.3. Simple layout of probabilistic earthquake ground motion (GM) hazard computation, and the associated equal probability response spectrum.

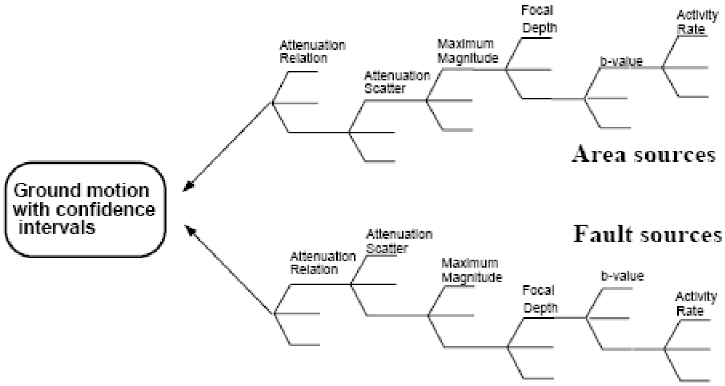


Fig. 2.4. Logic tree branches for seismic sources.

2.3.1. Theoretical framework

The model for the occurrence of ground motions at a specific site in excess of a specified level is assumed to be that of a Poisson process. This follows if the occurrence of earthquakes is a Poisson process, and if the probability that any one event will produce site ground motions in excess of a specified level is independent of the occurrence of other events. The probability that a ground motion level is exceeded at a site in unit time is thus expressed as:

$$P(Z > z) = 1 - e^{-\nu(z)}$$

where ν(z) is the mean number of events per unit time in which Z exceeds z. According to convention (McGuire, 1976) in probabilistic hazard analysis, the region around a site is partitioned into polygons, which constitute a set of area sources. Basic differences in seismicity and geology may exist between the zones, however, it is assumed that seismicity within each zone is sufficiently homogeneous to be treated uniform in the computations. This assumption applies even where non-seismological criteria have been used in the zone definition, e.g. geological structures. With N seismic sources, and seismicity model parameters Sn for each source n, the mean number of events pr. unit time in which ground motion level z is exceeded can be written as:

$$\nu(z) = \sum_{n=1}^{N} \nu_n(z|S_n)$$

where

$$\nu_n(z|S_n) = \sum_{i,j} \lambda_n(M_i|S_n)\ P_n(r_j|M_iS_n)\ G_n(z|r_jM_iS_n)$$

$\lambda_n(M_i \mid S_n)$ is the mean number of events pr. unit time of magnitude M_i ($M_i \in [M_{\min}, M_{\max}]$) in the source n with seismicity parameters S_n.

$P_n(z \mid M_i S_n)$ is the probability that a significant site – source distance is r_j, ($r_j \in (r_{\min}, r_{\max})$) given an event of magnitude M_i at distance r_j in source *n* with seismicity parameters S_n.

$G_n(z \mid r_j M_i S_n)$ is the probability that the ground motion level z will be exceeded, given an event of magnitude M_i at distance r_j in source *n* with seismicity parameters S_n.

The three functions $\lambda_n(M_i \mid S_n)$, $P_n(z \mid M_i S_n)$ and $G_n(z \mid r_j M_i S_n)$ model the inherent stochastic uncertainty in the frequency of occurrence and location of earthquakes, and in the attenuation of seismic waves.

Besides this natural uncertainty, there is also an element of uncertainty associated with the variability of the model parameters S_n. This source of uncertainty is accounted for by regarding the parameters S_n as random variables, whose discrete values are assigned with weights reflecting their likelihood. These discrete values represent branches in a logic tree for the seismic hazard model. At each node, probabilities are attached to the various branches. Consideration of the complete set of branches allows the probability distribution ν(z) to be calculated.

Given that the mean number of events per unit time for which Z exceeds z is expressed for example as $1/T_R$, where T_R is the return period (inverse of annual exceedance probability), then the number of events in a time period T (e.g. the life time of a certain construction) for which Z exceeds z is given by T/T_R and the probability for Z exceeding z during that life time T is given by:

$$P(Z > z) = 1 - e^{-T/T_N}$$

For a life time T of 50 years and a return period T_R of 475 years (annual probability of exceedance 0.211×10^{-2}) the probability for Z exceeding z becomes 0.1, corresponding to 90% probability that this size ground motion is not exceeded in 50 years.

With several seismic sources, described through particular model parameters, the mean number of events per unit time in which the ground motion level z is exceeded can be expressed specifically, involving functions that model the inherent stochastic uncertainty in the frequency and location of earthquakes, and in the attenuation of the seismic waves.

Besides this natural uncertainty, there is also an element of uncertainty associated with the variability of model parameters. This source of uncertainty is accounted for by regarding these parameters as random variables, whose discrete values are assigned weights reflecting their likelihood.

These discrete values represent branches in a logic tree for the seismic hazard model (see Fig. 2.4). At each node, probabilities are attached to the diverse branches, which are disjointed and exhaustive of possible choices. Consideration of the complete set of tree branches allows the probability distribution of ν(z) to be calculated.

Earthquake recurrence model

The recurrence rate of earthquakes is assumed to follow the cumulative Gutenberg-Richter relation:

$$Log\ N(M) = a - bM$$

where *N(M)* is the number of events per year with magnitude greater or equal than M. This relation appears with few exceptions to hold quite well, indicating a self-similarity of earthquakes.

In seismic hazard analyses a modified and truncated version of this relation is used, involving an engineering threshold magnitude M_{lim}, a limiting upper bound magnitude M_{max} for the source, a slope parameter β = b*ln(10) that describes the relation between the number of small and larger earthquakes, and an activity rate parameter $A=a(M_{lim})$ which describes the number of events on the source with magnitude equal to or greater than M_{lim}.

The activity rate parameter *a* is liable to vary substantially from one seismic source to another while the *b*-value is expected to be regionally stable, with variations less than the uncertainty limits. Faults which are separately included as seismic sources in addition to area sources may be attributed their own *b*-values, which need to bear no immediate relation to the values obtained from the regional recurrence statistics.

For both, fault and area sources, the maximum magnitude parameter M_{max} is very important, especially for sources with low *b*-values.

Strong-motion attenuation

Assuming the occurrence of an event of magnitude M_i at a site-source distance of R_j, the probability of exceedance of ground motion level Z needs to be defined.

From studies of strong-motion records, a log-normal distribution is found to be generally consistent with the data, with the mean having a form such as:

$$lnZ = c_1 + c_2 M_i + c_3 ln R_j + c_4 R_j$$

where Z is the ground motion variable and $c_1 - c_4$ are empirically determined constants. Also found from the recorded data is an estimate of the distribution variance.

2.3.2. Logic tree formalism

In the general seismic hazard model, weighted, discrete distributions are input for principal seismological and geological variables such as wave attenuation, source geometry, maximum magnitude, focal depth, *b*-value, and activity rate.

The attenuation parameters are assigned simultaneously for all area sources, while they may be separately assigned for individual faults, depending on directivity effects and nature of faulting. For fault sources, variations in geometry (both strike and dip) can be accommodated by inputting the different geometries with appropriate weights. For area sources, uncertainty in zonation can either be accommodated by varying the zone activity rate distributions, or by rerunning the program with alternative zone geometries; each zonation requires parameterization and hence is equivalent to a new problem.

For the individual seismic sources, both areas and faults, parameter variability in maximum magnitude, focal depth, *b*-value and activity rate can be introduced as shown in the logic trees (Fig. 2.4). For fault sources, the assignment of activity rates results from further tiers of branching, reflecting the significant uncertainty in associating recorded events with individual faults, the uncertainty in correlating slip-rate data with the occurrence of past earthquakes, and the primary uncertainty over whether a fault is active or not.

For each terminal node of the logic tree branches that stems from source *n*, having model parameters $S_n(m)$, the NPRISK program computes the probability weight function $P(S_n(m))$. These weight functions are then used to construct the probability distributions of the random variables $\nu_n(z)$, and the mean number of events per unit time in which the level z of ground motion is exceeded.

The probability distribution of $\nu_n(z)$ is close to lognormal for real seismic hazard problems of any complexity (Kulkarni et al., 1984), and estimates of its mean and variance allow confidence levels for the exceedance to be computed efficiently.

2.4. Implementation

General

The earthquake criteria development performed for this study is, as explained in more detail above, based on probabilistic seismic hazard analysis techniques designed to incorporate uncertainties (logic trees) and to quantify the uncertainties in the final hazard characterizations (confidence limits).

The procedure for identifying potential seismic sources in the project region comprise:

- An evaluation of the tectonic history of the region in light of available geological data and information.
- An evaluation of the historical and recent instrumental seismicity data in relation to the project region, emphasizing that these data are the primary empirical basis for conducting seismic hazard analyses.

The present study is building on knowledge and experience within the field of earthquake criteria development for numerous sites in different tectonic environments, thereby ensuring results which are comparable on a larger scale.

Geology

The general approach to this side of the seismic criteria development is to review relevant and available geological information in order to locate and characterize active and potentially active geologic structures, i.e., faults and/or segments of faults which may represent a potential seismic source that could influence the seismic hazard at the site.

Seismology

A seismic hazard analysis should be based on both the geological and seismological history of the region, including recent and historical seismicity, supplemented with paleoseismological information if available. The information called for here includes generally, besides the usual earthquake catalog, also information which can improve the understanding of the geodynamics of the region, such as earthquake rupture processes, mode of faulting, inferred stress field, etc.

Seismotectonic interpretation

The geological and seismological information is used to define models for the potential earthquake sources that could influence the hazard at the site. The main aspects of the source characterization are: (1) modeling of area sources based on the geologic history of the region in general and on earthquake occurrence statistics (historical and contemporary seismicity catalogs) in particular, and (2) modeling of fault-specific sources with three-dimensional geometry, if such detailed information is available.

The characterization of each seismic source will be as comprehensive as the data allows and will specifically incorporate the uncertainties in each source characteristic.

Maximum earthquake magnitudes are assessed using a combination of physical methods, historical seismicity and empirical evidence from geologically similar regions.

Ground motion models

The present earthquake hazard study requires the availability of earthquake ground motion models for peak ground acceleration and spectral velocity, for the whole frequency range of engineering interest. Such models include near field excitation as well as the attenuation with distance, and the scaling with magnitude here is essential inasmuch as a hazard estimate normally implies estimating effects of an earthquake not yet observed in the region considered.

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

Computational model

The actual seismic hazard computations for a specific site are based on integrated probabilistic contribution to the ground motion by the fault-specific and area sources modified by the seismic wave attenuation. The logic tree procedure is used to model the input parameters with different probabilities.

Hazard results and design criteria

The relationship between a range of ground motion levels and the associated annual exceedance probability (hazard curve) is established for each frequency, and a measure of uncertainty in the final results is made available in terms of confidence limits.

An essential element of the present earthquake hazard methodology is that seismic loading criteria are evaluated in terms of equal-probability (equal hazard) spectra. This means that each frequency is evaluated independently, with its own uncertainty estimate.

The seismic loading criteria (only PGA are estimated) are specifically developed for bedrock outcrop (site with no soil), and provided in the form of Peak Ground Acceleration. Design (response) spectra for the required annual exceedance probabilities may then be developed based on the PGA values, and in certain cases accompanied with sets of real time histories (earthquake recordings), appropriately scaled to match the spectra. The latter is done only when specific advanced design analysis is conducted.

3. Geology

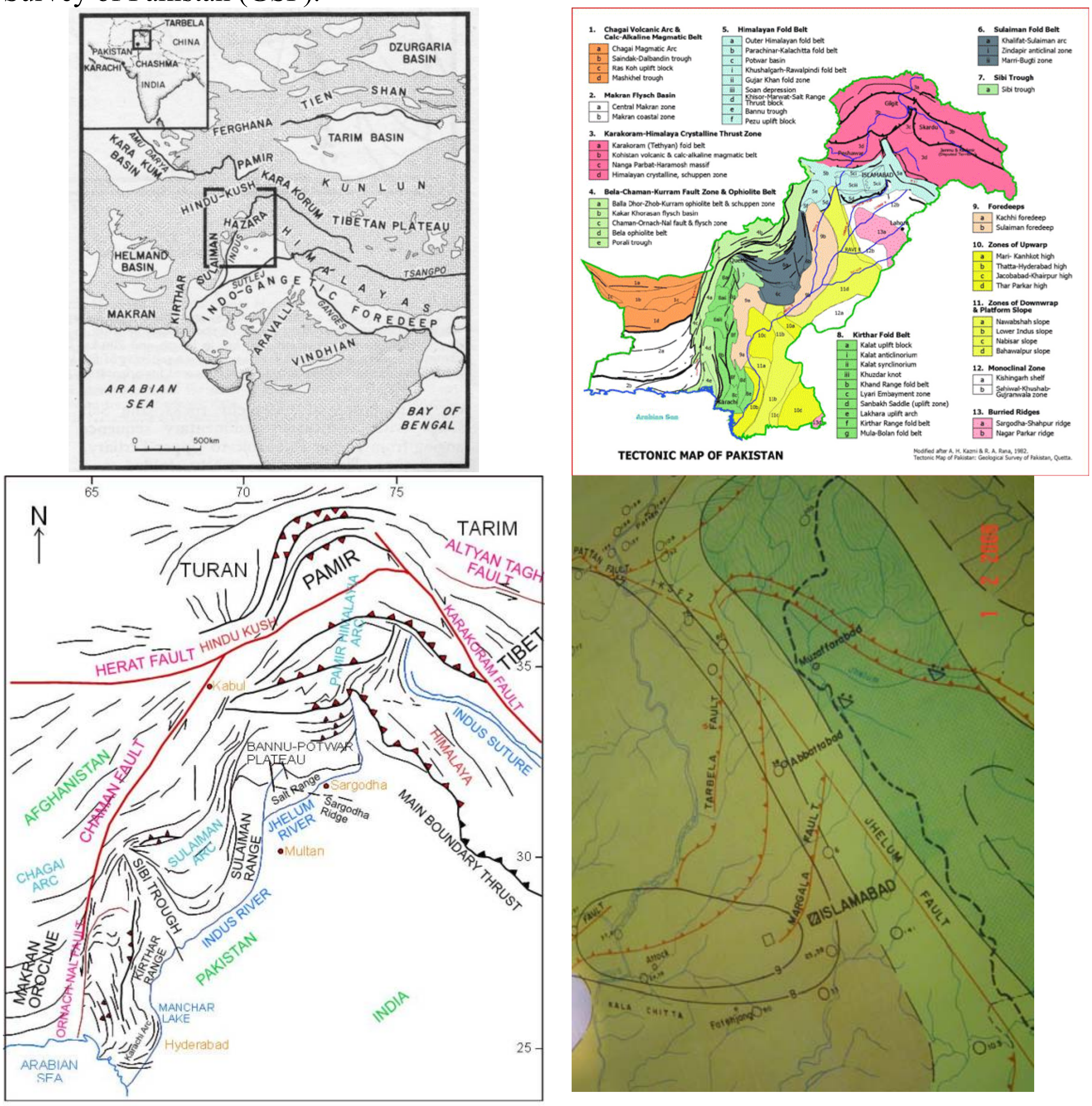
There is a continuous chain of mountains in the north and northwest of Pakistan; Himalayas are in the north, Hindukush and Suleman mountains in the northwest. Pakistan, as the surrounding countries, is seismically active and there is a history of large earthquakes. The seismic monitoring is presently limited to a nationalø network of 6 stations (2 digital) operated by the Pakistan Meteorological Department (PMD).

The mountains surrounding Pakistan to the northeast, north and northwest were formed during the middle and upper tertiary ages. Their curvilinear from is characteristic; all shaped as circular arcs with their convexity toward the southern and eastern plains. These arcs of smaller radii succeed one another at short intervals

The three main mountain arcs are i) the Hazara and Koh-e-safed, ii) the Sulaiman terminating near Quetta and iii) the Kirthar and Makran range. The seismological data point to these mountain ranges as the main source of earthquakes, which hence can be divided in four major zones: the Hindukush Region, Makran Coast, Karakoram Range and the Baluchistan Zone. We shall in the following mainly focus on the Karakoram and Hindukush seismicity.

3.1. Regional geological setting

The regional tectonic setting is best seen from Fig. 3.1 prepared by the Geological Survey of Pakistan (GSP).



Major Tectonic on and around the northwest of the Indo-Pakistan subcontinent

Fig. 3.1. Upper left: Tectonic overview of the larger region. Upper right: Tectonic map of Pakistan. Lower left: Mapped faults in the region under focus. Lower right: Mapped faults in the region close to Islamabad.

The regional deformation is nicely depicted in Fig. 3.1 and Fig. 3.2. The encircled areas (Fig. 3.2) indicate the two major earthquake disasters in Pakistan over the last 100 years, and both areas have tectonic similarity in the shape of the deformation zone (going into a compressive north-bend). For both areas a peculiar similarity exists: the northeastern regions of these bends are more active than the northwestern and western regions.

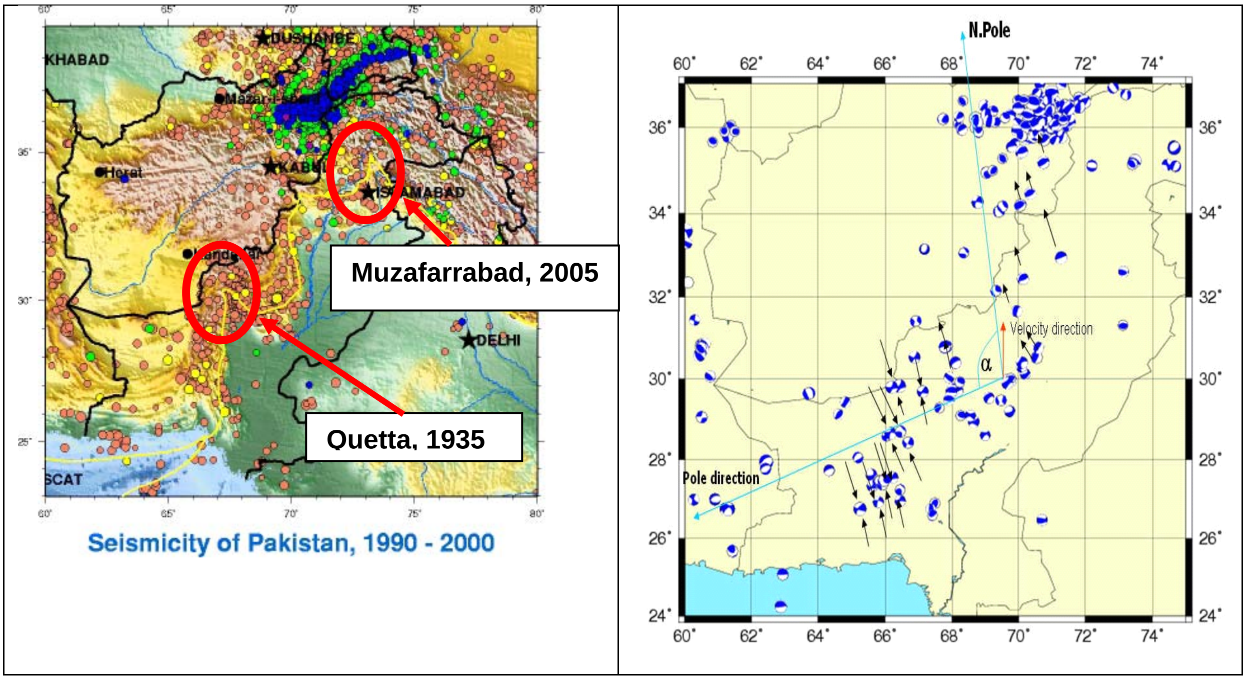


Fig. 3.2. Left: Seismicity pattern of Pakistan with yellow line indicating the deformation boundary (boundary trench). The circles indicate the names and sites of the two most devastating earthquakes over the last centennial. Adapted from USGS web page. Right: Regional deformation image of Pakistan. CMT solutions 1977-2003 analyzed by Ameer Hyder.

3.2. Faults and regional tectonics

It has been found (e.g. Nakata et al., 1991) that the main faults in Pakistan seem to be seismically quiet (locked) except at times of the large damaging earthquakes. It seems that this silence (or seismic gap) is more true for the Himalayas than for many other seismically active areas, and in terms of seismic hazard it represents the problem that locked areas may appear inactive for longer time periods than our monitoring record.

Also, while a thrust regime clearly dominates in several places, it is often difficult or impossible to associate specific seismic activity with specific fault traces, and this leads to the conclusion that many faults are blind.

Of the faults detailed below we have in the present hazard study only found it adequate to model the Jehlum fault. The other faults known to be active were too distant from Islamabad and Rawalpindi to warrant such detailed modeling.

The detailed description below is largely based on the “Seismic Risk Map of northern Pakistan” by the National Geo-data Centra, Geological Survey of Pakistan, 1988.

Jehlum fault

It is a north-south trending sinistral strike-slip fault (wrench fault), which follows the western margin of the axial zone of the Hazara- Kashmir syntaxial bend. The fault was reported by original researchers to extend along the Jhelum river and further southwards to Chaj Doab. Between Muzafarabad and Koala, this fault apparently dislocates the MBT and a left lateral offset of about 31 km is indicted on the western limb of the syntaxis (see Fig. 3.1). In this region of Murree, Abbotabad and Hazara the geological formations are highly deformed and displaced several km southwards.

A concentration of seismic activity is seen along the Jhelum River North of Mangla. This seismicity is observed to align not only along the mapped portion of the Jehlum Fault, but also extends North and south of this mapped fault. Towards the southern side this seismicity pattern appears to extend along the Dil Jabba thrust which may suggest that this portion of Jhelum fault could be a northward extension of the Dil Jabba thrust (just as MBT turns North near Kohala). Based on seismicity the fault is active and the nearest trace is taken as 15km, north of the Mangla Dam project (Mahdi 2005).

Tarbela fault

It is strike slip fault which passes below the Tarbela dam and separates the Salkhlala and Tanawal formations on the west bank of the Indus River from the Abbotabad formation. The Tarbela segment of the MBT is regarded as presently inactive (Dr. Kausar, pers. communication).

Margalla Fault

It is an important fault, which runs NE-SW and joins the main boundary thrust (M.B.T) in the Hazara-Kashmir syntaxial zone. It passes north of Islamabad on the southern piedmont slopes of the Margalla Hills. As a result of this fault, the Datta formation and the Saman-Suk limestone are trusted over the Lockhart limestone. There is no record or indication of movement along the Margalla fault.

Pattan fault

This fault trends roughly NW-SE and is approximately 25 km long, and may be regarded as a segment of the MMT. It is an active fault.

The M=6.0 Pattan earthquake of Dec 28, 1974 occurred where the MMT meets with the Indus Kohistan Seismic zone (IKSZ).

The main Karakoram thrust fault (MKT)

The main Karakoram thrust or the northern mega sheet represents the collision zone of the southern margin of the Eurasian plate in Asia and extends into Baltistan through Hashupa and Machie in the Shigar and Shyok valleys, respectively. MKT is a high angle seismically active thrust with a large number of earthquakes of low to median intensity E/Qs (Seismic Risk Map of Northern Pakistan, 1988, PGS).

The main Mantle thrust fault (MMT) andc the Main Boundary thrust (MBT)

The main mantle thrust or the southern mega shear spans an area of about 400. sq km through Diyamir, Kohistan, Swat, Dir and Bajaur. The main boundary thrust is a distinct tectonic feature along the entire Himalayan Belt.

The MBT loops around the Hazara syntaxial zone. It represents the major zone of current deformation and the largest earthquakes. The MBT stretches from the Afghan border, and can be traced nearly continuously to Assam in eastern India. It is the single most potent earthquake source in the Himalayas.

Raikot fault

It is an active fault, which is characterized through a zone of breccias 5-10 m thick in the Holocene fan gravels developed at the foot of Nanga Parbat massif. It appears to reflect a steeply dipping fault with a down throw towards north. A line of hot springs delineates the trace of fault.

3.3. Deformation Fault Models

Himalaya is the model area on the earth for active deformation, and the region in focus is as active as other comparable Himalayan regions. In this active regime we are, however, confronted with a rare problem: when the deformation is as fast as in the Himalayas, new faults are constantly created, and old active faults are left in inactivity so quickly that it is difficult from solely geological information to know if a certain fault is currently active. This situation can be alleviated with very dense seismic networks deployed over a long time, or through GPS monitoring in dense grids. None of these options could provide results at the time of this work, and we were confronted with a number of faults in the vicinity of Islamabad that could potentially be active. To the northwest of Islamabad we have the following reverse faults:

1. The Margalla fault which delineates the Margalla hills and is most often recognized as a splay of the Main Boundary Thrust (MBT). This fault is immediately north of Islamabad with a potential dramatic impact on the seismic hazard.
2. The MBT which runs parallel and north of the Margalla fault.
3. The Tarbela fault which runs along the Tarbela river

To the northeast of Islamabad runs the MBT in a southeasterly direction with several splay faults. These regions have shown a constant seismic activity, and it was this fault which ruptured in the M=7.6 Muzafarrabad earthquake. The historical seismicity depicts this as a very active deformation zone. To the east of Islamabad runs the prominent Jehlum strike slip fault which is regarded as a main boundary for the Himalayan compression in this area.

The Jehlum fault seem to represent a boundary for the deformation, such that the eastern parts are subject to constant deformation and historical earthquake activity, whereas the western and northwestern parts show significantly less activity.

This concept is confirmed by the Pakistan Geological Survey through Dr. Kausar (personal communication) who pointed out that the Margalla, Tarbela and MBT fault to the northwest of Islamabad are currently inactive, whereas very strong activity is found on the MBT northeast of Islamabad (Muzafarrabad segment), and clear evidences of deformation activity has been observed at the northern end of the Jehlum fault (Tapponier, indirect communication). While the degree of activity is not yet resolved for the Jehlum fault, the indicators of present day activity are relatively clear. From the geometry of the deformation, any shortening of the crust along the Muzafarrabad segment of the MBT will increase stresses on the northern segment of the Jehlum fault.

For the time being, very few hard evidences of deformation of the region north of Islamabad have been quantified, and following the October 2005 disastrous earthquake several field surveys with GPS measurements and fault trenching are planned in the coming years.

From the above we decided in this study to include only the northern segment of the Jehlum fault in a quantitative fault modeling for the seismic hazard analysis.

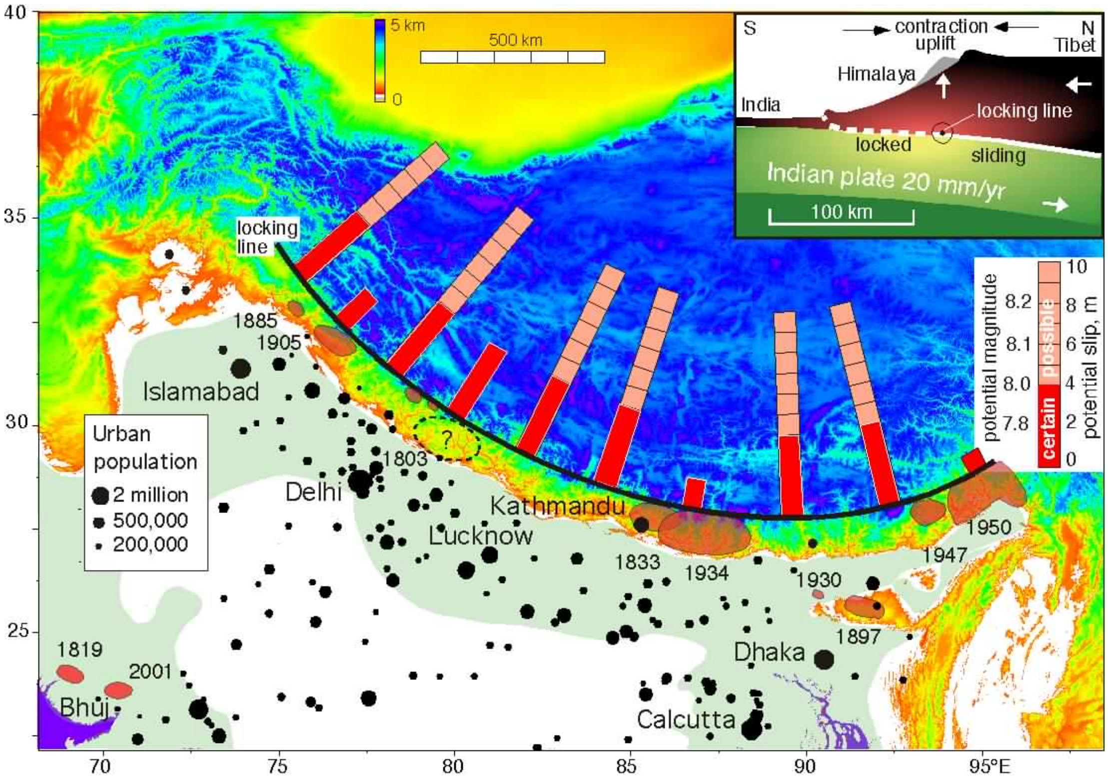


Fig. 3.3. This view of the Indo-Asian collision zone shows the estimated slip potential along the Himalaya and urban populations south of the Himalaya (U.N. sources). Shaded areas with dates next to them surround epicenters and zones of rupture of major earthquakes in the Himalaya and the Kachchh region, where the 2001 Bhuj earthquake occurred. Red segments along the bars show the slip potential on a scale of 1 to 10 meters, that is, the potential slip that has accumulated since the last recorded great earthquake, or since 1800. The pink portions show possible additional slip permitted by ignorance of the preceding historic record. Great earthquakes may have occurred in the Kashmir region in the mid 16th century (21) and in Nepal in the 13th century (8). The bars are not intended to indicate the locus of specific future great earthquakes, but are simply spaced at equal 220-km intervals, the approximate rupture length of the 1934 and 1950 earthquakes. Black circles show population centers in the region; in the Ganges Plain, the region extending ~300 km south and southeast of the Himalaya, the urban population alone exceeds 40 million. (inset) This simplified cross section through the Himalaya indicates the transition between the locked, shallow portions of the fault that rupture in great earthquakes, and the deeper zone where India slides beneath Southern Tibet without earthquakes. Between them, vertical movement, horizontal contraction, and microearthquake seismicity are currently concentrated. Caption cited from Bilham et al. (2001).

3.4. Deformation zones and seismotectonics

The principles of PSHA are that “the future is predicted from the past” applied in the sense that past earthquake occurrence provide the basis for understanding where the future earthquakes will occur. While it is true that earthquakes zones seem to be constant, and that the majority of earthquakes occur in zones where they are experienced and expected, it is also recognized that large earthquakes may occur in unexpected regions. The PSHA procedure partly reflects this uncertainty by including source zones also with low seismic activity.

It is here relevant to mention that two other alternatives for seismic hazard quantification that are now approaching:

1. With the increasing precision and decreasing costs in GPS measurements the possibility of measuring detailed local deformations emerge as an important tool for delineating zones of possible future earthquakes.
2. With the increasing knowledge of regional deformation combined with improved models for slip estimation in large earthquakes it becomes possible to estimate the recurrence time between large regional earthquakes and the possible location and region of future large events.

Due to lack of high quality data we could in the present PSHA analysis not includ the use of such data. However, such data may be a very interesting subject for future hazard investigations, and one would then expand on the ideas forwarded by Bilham et al. (2001) in his estimation of growing earthquake risk in the Himalayas as reproduced in Fig. 3.3.

4. Seismology

This part is primarily concerned with the analysis of the records of past earthquakes.

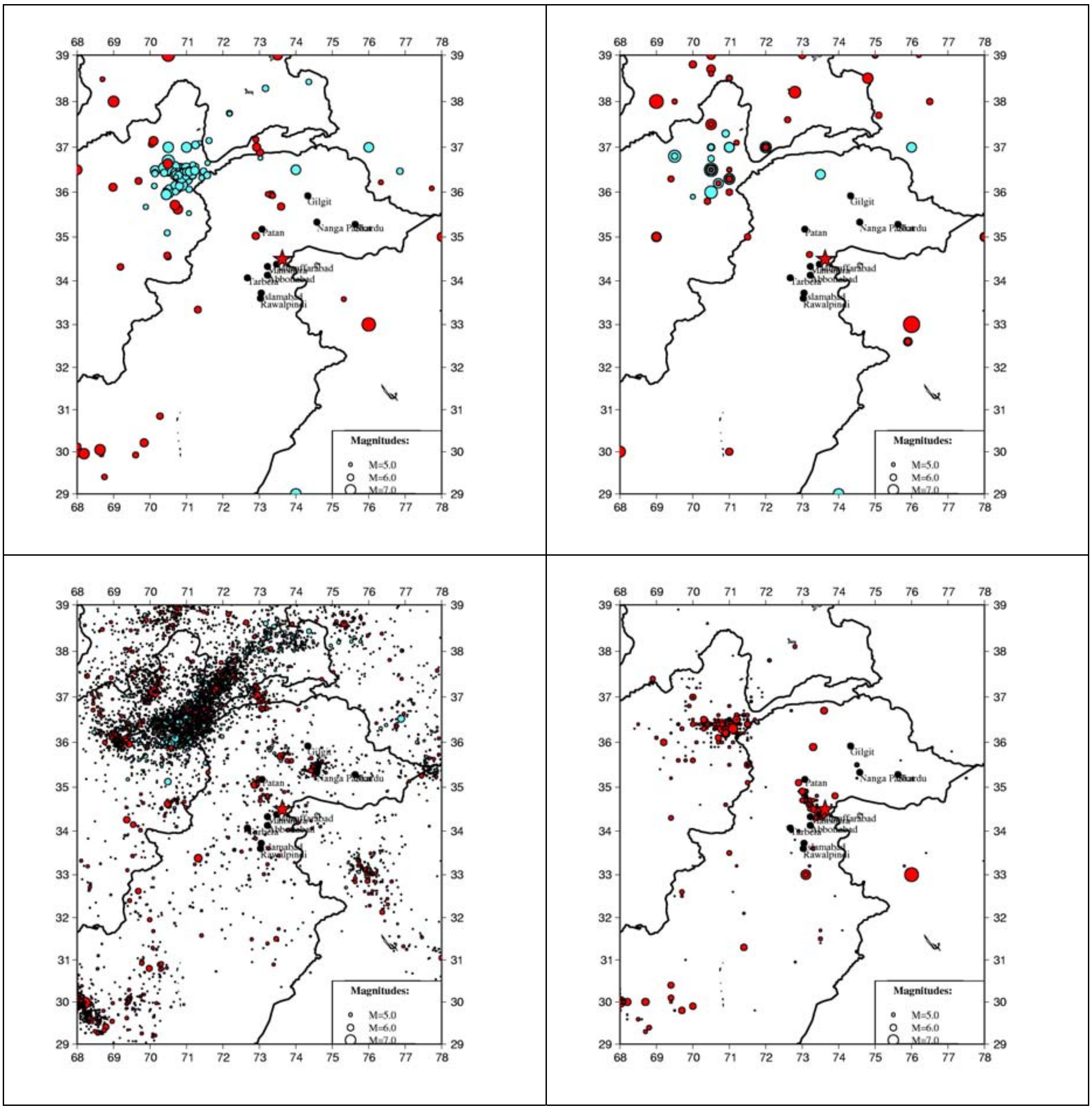
4.1. Databases

The following earthquake catalog databases were sought during this study:

1. The ISC database
2. The USGS, PDF database covering the time period 1973 through 2005.
3. The EHB global database covering the time period from 1900 through 1999.
4. The USGS particular databases on large earthquakes in the region.
5. The NORSAR database, which consists of reports from observatories globally
6. The PMD database covering historical earthquakes and the most recent instrumental earthquakes. Depth information was available only for the last four years.

The various catalogs are shown in Fig. 4.1.

The EHB database is likely to be the qualitatively best database in terms of magnitudes and location precision, however, with relatively few earthquake reports. The PDE catalog is very complete from 1973, and is partly based on data provided to USGS from PMD. The USGS particular event databases and the NORSAR databases were regarded as too sparse to be useful except for consultations on special issues. The ISC database was likewise found very sparse.



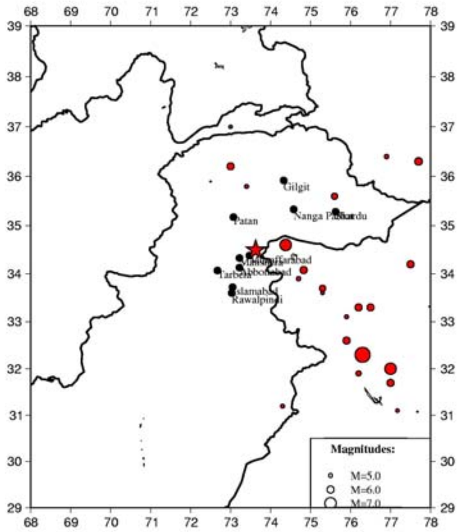


Figure 4.1. Earthquake databases for the region as consulted during the present project. Upper left: EHB database; Upper right: NORSAR database; Mid left: PDE database; Mid right: PMD database; Lower left: Significant earthquakes from NEIC. Note the PMD catalog had reliable depth information only for the last years. In all the plots the red star indicates the Muzafarrabad epicenter and the black dots with names indicate cities or important sites.

Neither of the databases analyzed and referenced above satisfy a high quality database, however, realizing that quantification of the seismicity is necessary it was clear that the PDE database, in spite of deficiencies was best suited as a basis for the quantification in each of the source zones to be defined.

4.2. The largest earthquakes

The principal events in the PMD database are tabulated in Table 4.1, showing the complete historical database from pre-historical times until 1903, and the major damaging earthquakes in the 20'th century. Fig. 4.2 shows an extract of Table 4.1 with one panel focusing on the largest earthquakes around Islamabad and Rawalpindi as does Table 4.2.

DATE	LAT(N)	LONG(E)	INTENSITY	REMARKS
25 A.D	33.7	72.9	X	TAXILA EARTTHQUAKE The main centre of Budhist Civilization at that time was turned into ruins. Epicentre of the earthquake was around 33.7 N, and 72.9E. Maximum documented Intensity was X.
50 A.D	37.1	69.5	VIII_IX	AIKHANUM EARHQUAKE Epicentre of the earthquake was around 37.1 N, and 69.5E. Maximum documented Intensity was VIII-IX . Caused extensive damage in Afghanistan, Tajikistan and N.W.F.P and was felt upto N.India.
893-894AD	24.8	67.8	VIII_X	DABUL EARTHQUAKE Epicentre of the earthquake was around 24.8 N, and 67.8E. Maximum documented Intensity was VIII-X. An Indian ancient city on the coast of Indian ocean was completely turned into ruins. 1,80,000 people perished.
6/7/1505	34.6	68.9	VIII_IX	HINDUKUSH EARTHQUAKE Epicentre of the earthquake was around 34.6 N, and 68.9E. Maximum documented Intensity was VIII-IX. It was an immense Earthquake causing famine and extensive damage & loss of life in Afghanistan.
3/1/1519	34.8	71.8	VI-VII	JANDOLVALLEYEARTHQUAKE Jandol valley was severely rocked. Epicentre of the earthquake was around 34.3 N, and 71.8E. Maximum documented Intensity wasVI-VII.

May, 1668	24.8	67.6	VIII-IX	SAMAJI OR SAMAWANI Town of Samaji or Samawani sank into ground. 80,000 houses destroyed. Epicentre of the earthquake was around 24.8 N, and 67.6E. Maximum documented Intensity was VIII-IX.
4/6/1669	33.4	73.2	VI-XI	MANDRA EARTHQUAKE Epicentre of the earthquake was around 33.4 N, and 73.3E. Maximum documented Intensity was VII .
23/6/1669				Attock Earthquake
16/6/1819	23.3	68.9	IX-X	RUNN OF CUTCH It reduced to ruins.2000 people died. Epicentre of the earthquake was around 23.3 N, and 68.9E. Maximum documented Intensity was IX-X.
24/9/1827	31.6	74.4	VIII-IX	LAHORE EARTHQUAKE In this earthquake the fort kolitaran near Lahore was destroyed.About 1000 people perished.A hill shaken down into river Ravi.
6/6/1828	34.1	74.8	X	KASHMIR EARTHQUAKE In this earthquake 1000 people died and 1200 houses destroyed.
1831	33.5	72.0	IV-VII	HINDUKUSH EARTHQUAKE It was severe earthquake felt from Peshwar to D.G Khan Maximium documented Intensity was VII at Peshwar VI at Srinagar and IV at D.G Khan.
22/01/1832	36.9	70.8	VIII-IX	HINDUKUSH EARTHQUAKE It was severe earthquake Which rocked Afghanistan, Northern and central parts of Pakistan and NW India.Maximium documented Intensity was VIII-IX at Kalifjan,Jurm,Kokcha Valley,and VI at Lahore.
21/2/1832	37.3	70.5	VIII-IX	HINDUKUSH EARTHQUAKE The epicenter of this earthquake was in Badakhshan Province.Earthquake felt at Lahore and NW India.
19/2/1842	34.3	70.5	VIII-IX	HINDUKUSH EARTHQUAKE Epicentre of the earthquake was near Kabul .Maximium documented Intensity was VIII-IX Alingar valley, Jalalabad and Tijri and VI-VII at Teezeen and VII-VIII at Budheeabad.The earthquake was felt from Kabul to Delhi Over an area of 2,16,000 sq.miles.Jalalabad and Peshawar damaged,.
19/6/1845	23.8	68.8	VII-VIII	RUNN OF CUTCH Documented epicentre of this earthquake was lie between 23.8 N, 68.8 E, and Maximium intensity was VII-VIII.Lakhpat was badlt effected.
Jan,1851	32.0	74.0	VI-VIII	PUJAB PLAIN EARTHQUAKE Maximium Documented intensity was VIII ,and VI-VII at Wazirabad ,Ferozpur and Multan,VI at fort Munro.
19/4/1851	25.1	62.3	VII	GAWADAR EARTHQUAKE Epicentre of the earthquake was around 25.1 N, and 62.3E. Maximum documented Intensity was VII at Gwadar.Another earthquake of same intensity occurred on 25th July,1864 at Gawadar.
24/1/1852	34.0	73.5	VIII	MURREE HILLS EARTHQUAKE Epicentre was in Murree hills and Kajnan about 350 people died.Maximium Documented Intensity was VIII.
1867	29.2	68.2	VII	LAHRI EARTHQUAKEThe epicentre of earthquake was around 29.2 N,68.2 E, Maximium Documented Intensity was VII at Lahri.
10/11/1868	32.5	71.3	VIII	BANNU EARTHQUAKE The epicentre of earthquake was around 32.5N,71.3 E. Maximium Documented Intensity was VIII at Bannu.
11/8/1868	34.0	71.6	VII-VIII	PESHAWAR EARTHQUAKE The epicentre of earthquake was around 34. 0N,71.6E,near Peshwar. Maximium Documented Intensity was VII-VIII.Another earthquake same Intensity Occurred same place in April 1869.

20/12/1869	33.6	73.1	VII-VIII	RAWALPINDI EARTHQUKE The epicentre of earthquake was around 33.6N,73.1E. Maximium Documented Intensity was VII-VIII at Rawalpindi,V-VI at Lawrancepur and Attock.It caused cracks in walls in many houses at Rawalpindi.
April,1871	34.0	76.0	VII-VIII	KASHMIR EARTHQUAKE The epicentre of earthquake was around 34.0N,76.0E,in Kashmir. Maximium Documented Intensity was VII-VIII. It was also felt with Intensity VI at Rawalpindi and Murree.
20/5/1871	36.9	74.3	VII-VIII	GILGIT EARTHQUAKE The epicentre of earthquake was around 36.9N,74.3E,in former Gilgit agency. Maximium Documented Intensity was VII-VIII.
18/10/1874	34.5	69.2	IX	KABUL EARTHQUAKE The epicentre of earthquake was around 34.5N,69.2E .Maximium Documented Intensity was IX at Kabul,Jabal-al-saraj and Gulbahar and VIII in Kohistan area of N.W.F.P.
12/12/1875	31.6	74.4	VII-VIII	LAHORE-PESHAWAR EARTHQUAKE The epicentre of earthquake was around 31.6N,74.4E .Maximium Documented Intensity was VII-VIII at Peshawar and Lahore.
2/5/1878			VII-VIII	KOHAT-PESHAWAR EARTHQUAKE The epicentre of earthquake was between Kohat and Peshawar. .Maximium Documented Intensity was VII-VIII at Kohat and Peshawar,VI-VII at Attock ,Abbotabad,Rawalpindi and Jhelum,V-VI at Bannu,Nowshera,Mardan,Lahore and Simla.
30/5/1885	34.1	74.8	IX-X	KASHMIR EARTHQUAKE The epicentre of earthquake was around 34.1N,74.8E .Maximium Documented Intensity was IX–X in the epicentral area.VIII-IX at Sopur.Gulmarg,Gingal and Srinagar.VI-VII at Punch,Muzzafarabad area.Extensive damage was about 47 sq.miles between Srinagar,Baramula and Gulmarg.Total felt area was 1,00,000 sq.miles.About 3000 people parished and some villages were completely destroyed.
6/6/1885	34.2	75.0	IX-X	KASHMIR EARTHQUAKE The epicentre of earthquake was around 34.2N,75.0E .Maximium Documented Intensity was IX-X.
28/12/1888	30.2	67.0	VIII-IX	QUETTA EARTHQUAKE The epicentre of earthquake was around 30.2N,67.0E, at Quetta.Maximium Documented Intensity was VIII-IX.
1889	27.7	67.2	VIII	JHALAWAN EARTHQUAKE The epicentre of earthquake was around 27.7N,67.2E at Jhalawan .Maximium Documented Intensity was VIII.
1890	30.4	68.6	VII	LORALAI EARHQUAKE The epicentre of earthquake was around 30.4N,68.6E .Maximium Documented Intensity was VII at Loralai.
20/12/1892	30.9	66.4	VIII-IX	CHAMAN EARTHQUAKE The epicentre of earthquake was around 30.9N,66.4E near Chaman.Maximium Documented Intensity was VIII-IX at Chaman and VII at Sanzal. In this earthquake great damage to buildings,bridges,railoads and other structure etc.The earthquake was caused by the movement of Chaman fault on the west bank of Khojak range passing through the north west railway between Shelabagh and Sanzal.At Shelabagh the railway station building was severly damaged.
13/2/1893	30.2	67.0	VIII-IX	QUETTA EARTHQUAKE The epicentre of earthquake was around 30.2N,67.0E .Maximium Documented Intensity was VIII- IX at Quetta.
25/11/1893			VI-VII	PESHAWAR-NOWSHERA EARTHQUAKE The epicentre of earthquake was between Peshwar and Nowshera .Maximium Documented Intensity was VI-VII

				at both places.
1900	30.4	67.0	VIII	QUETTA-PASHIN EARTHQUAKE The epicentre of earthquake was around 30.4N,67.0E .Maximium Documented Intensity was VIII.
20/1/1902	35.9	71.8	VII-VIII	CHITRAL EARTHQUAKE The epicentre of earthquake was around 35.9N,71.8E near Chitral.Maximium Documented Intensity was VII-VIII.
1902	30.6	66.8	VII	GULISTAN-PASHIN EARTHQUAKE The epicentre of earthquake was around 30.4N,67.0E .Maximium Documented Intensity was VIII VII.
23/12/1903	29.5	67.6	VII	DADHAR EARTHQUAKE The epicentre of earthquake was around 29.5N,67.6E .Maximium Documented Intensity was VII.
04-04-1905	33.0	76.0	8.0	20,000 people killed at sialkot, all the houses were cracked and felt Afghanistan to Bengal.
21-10-1909	30.0	68.0	7.2	The villages of Baga, shahpur and Bellpat were destroyed and felt at Kachi Balochistan.
25-08-1931	30.3	67.0	7.0	Felt at Shahrig Balochistan. Buildings were damaged to some extended In Quetta pucca bricks building were slightly cracked.
27-08-1931	29.8	67.3	7.4	Felt at Much Balochistan and also felt over an estimated area of 3,70,000 sq. miles Bridges were destroyed.
31-05-1935	29.5	66.8	7.5	Felt area was approx. 1,00,000 sq. miles max intensity was X-XI. 30,000 victims. The cities of Quetta, Kalat & Mastung were completely destroyed.
28-11-1943	24.5	63.0	8.6	The earthquake which shock Makran Coast Balochistan, Sind and parts of the Punjab serious loss of lives and property was also reported from Ormara, about 130 miles from the epicenter. Manora Tower was cracked by the shocks.
07-02-1966	29.8	69.7	6.0	Felt in Barkhan Balochistan. About 150 persons injured and 30,000 person's affected and 5,000 houses damaged.
28-12-1974	35.1	72.9	6.0	Felt at Rawalpindi Islamabad and Lahore. About 5300 persons killed 17,000 injured and 93,000 persons were affected. Thousands houses destroyed. Ambraseys et al. !975) estimated 700-1500 casualties.
26-01-2001	23.4	70.2	6.9	Southern India. At last 20,005 people killed, 166,836 injured, approximately 339,000 buildings destroyed and 783,000 damaged in the Bhuj- Ahmadabad- Rajkot area and in Gujrat. Many bridges nd roads damajed in Gujrat. At least 18 People killed and some injured in Southern Pakistan. Felt throughout northern India and much of pakistan. Also felt in Bangladesh and Western Nepal.

Table 4.1. The historical database from pre-historical times until 1903, and the major damaging earthquakes in the 20'th century. PMD database. Note: Complete only for northern areas.

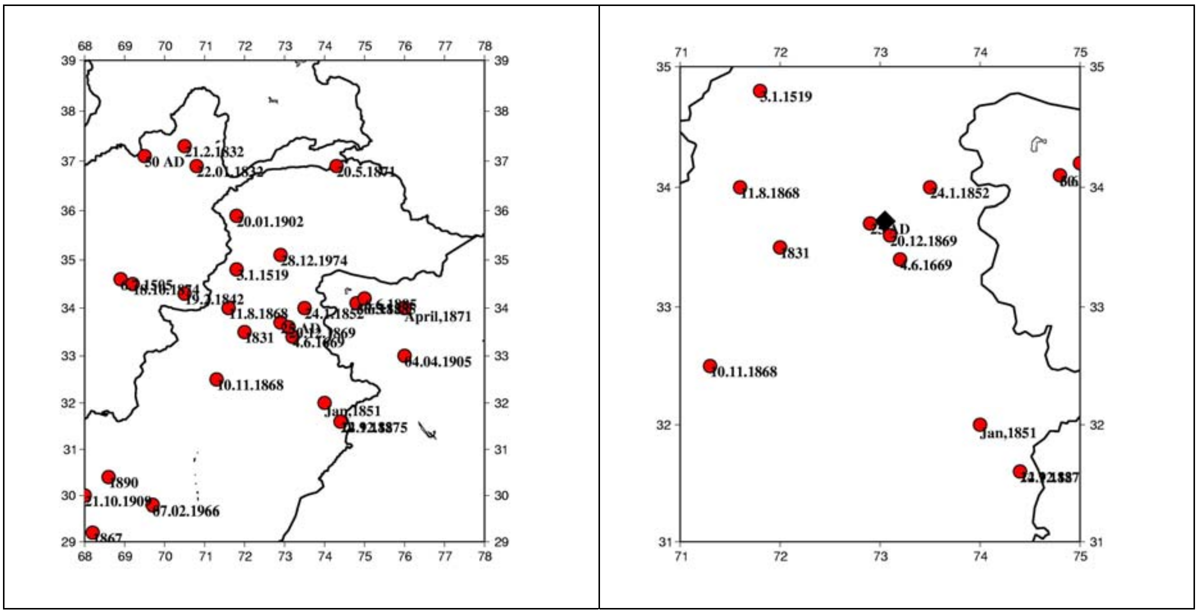


Figure 4.2. Left: Historical large earthquakes in the region. Right: Large historical earthquakes near Islamabad (indicated with black diamond).

25 A.D	33.7	72.9	X	TAXILA EARTTHQUAKE The main centre of Budhist Civilization at that time was turned into ruins. Epicentre of the earthquake was around 33.7 N, and 72.9E. Maximum documented Intensity was X.
4/6/1669	33.4	73.2	VI-XI	MANDRA EARTHQUAKE Epicentre of the earthquake was around 33.4 N, and 73.3E. Maximum documented Intensity was VII .
24/1/1852	34.0	73.5	VIII	MURREE HILLS EARTHQUAKE Epicentre was in Murree hills and Kajnan about 350 people died. Maximium Documented Intensity was VIII.
20/12/1869	33.6	73.1	VII-VIII	RAWALPINDI EARTHQUAKE The epicentre of earthquake was around 33.6N,73.1E. Maximium Documented Intensity was VII-VIII at Rawalpindi,V-VI at Lawrancepur and Attock.It caused cracks in walls in many houses at Rawalpindi.

Table 4.2. The historical damaging data from pre-historical times as collected by PMD near Islamabad.

4.3. Database analysis

Following the decision to use the PDE database as the main (but not sole) basis for quantification of the seismicity it was necessary to conduct analysis of the quality of that database, among others in terms of swarm activity and in terms of catalog completeness.

4.3.1. Aftershocks and swarms

The PSHA methodology is based on individual independent earthquake occurrence (the assumption of Poissonian earthquake occurrence), and it was hence done an analysis to identify possible swarms in the PDE database.

The main sequence identified in Fig. 4.3 corresponds to fore and aftershocks to the 1997, Feb. 27 M=7.3 earthquake near Quetta, and is hence not affecting the assumed

Poisson distribution in our target area. While other time clusters are clearly recognized, they are evaluated to be insignificant compared to the overall distribution, and insignificant for the quantification.

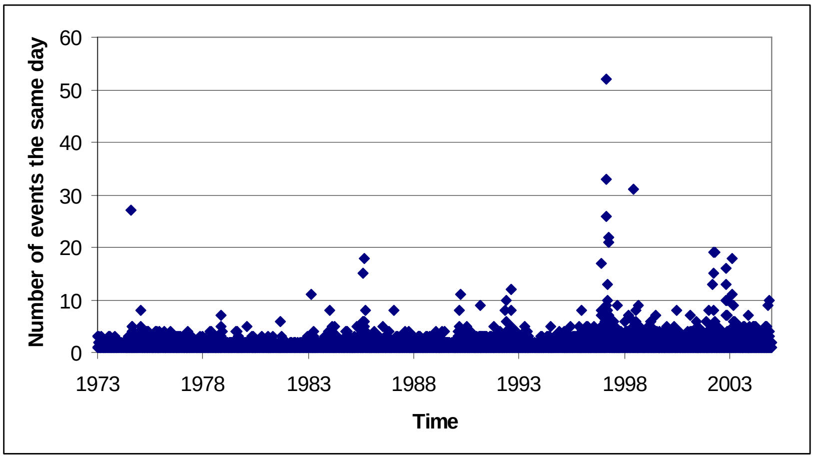


Fig. 4.3. PDE data analyzed for identifying time-space clusters that strongly violates the Poissonian assumption for earthquake occurrence.

4.3.2. Completeness

The time-magnitude plots were made for the catalogs from PMD and PDE as shown in Fig. 4.4. The figure demonstrates that the PMD catalog can be regarded as complete for M> 4.5 only from the late 1980's, whereas the PDE catalog for the same period can be regarded as complete for M>4 since 1973 when the catalog starts.

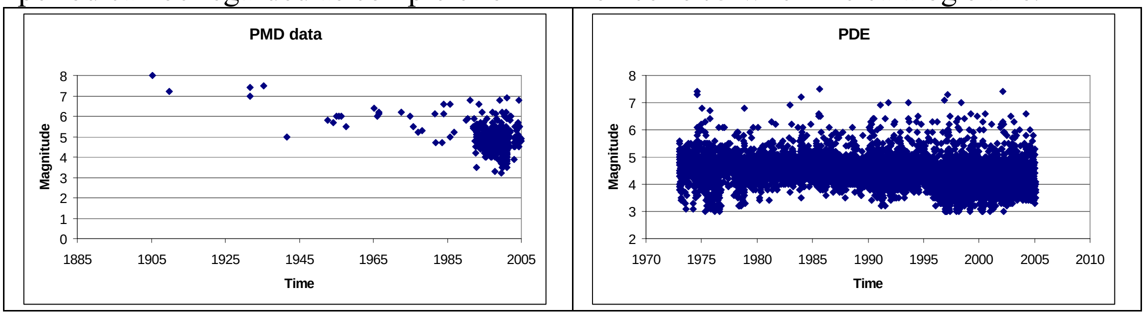


Fig. 4.4. Time-Magnitude plots for two catalogs for the identification of magnitude completeness thresholds. Left: PMD data. Right: PDE data collected for the region 29-39N and 68-78E. For both catalogs the space windows in Fig. 4.5 were analyzed.

4.3.3. Focal depths

While the PMD data is regarded as most interesting since they are collected at the local agency, the lack of depth information for the bulk of the data precludes the use of these data in the regression analysis.

The EHB data is regarded as the most reliable both in epicenter and depth determination. These data show (see Fig. 4.1) that the deep earthquakes are nearly entirely confined to the Hindu Kush region, where they are also prevalent.

4.3.4. Magnitudes

The PDE catalog is provided as Mb magnitudes for the lower magnitude events and with Ms and partly Mw for the larger events. With the general uncertainty of magnitude estimates, and the specific uncertainties of location and magnitudes for alternative catalogs in this region we regard this mixture of different magnitudes as a minor problem, and have consequently used the reported magnitudes.

5. Seismotectonic Interpretation

Based on the above geotectonic, and structural geology and earthquake information the division into eleven distinct source zones were made. In making this division the basic principles were followed:

- Each zone should be large enough to allow for a reasonably stable assessment of recurrence parameters.
- The zones should cover all areas where the seismicity could have some influence on the seismic hazard, which normally means 200-300 kilometers around the site, depending on activity level.
- The zonation should, if required, allow for possible regional differences in seismogenic conditions: focal depths, maximum magnitudes and faulting mechanisms.
- The zonation should be consistent with the regional geology and tectonics.

5.1. Seismic provinces and area source definition

Based on the previous discussions a seismic zonation divided the region into 11 shallow zones and one deep zone (Hindu Kush), and the zones were defined as shown in Fig. 5.2. The deep Hindu Kush earthquakes are so far from the target cities of Islamabad and Rawalpindi that they have been ignored in the computational model since this seismicity, though prominent, does not have any influence on the seismic hazard of the target cities. The eleven defined zones are described in Table 5.1.

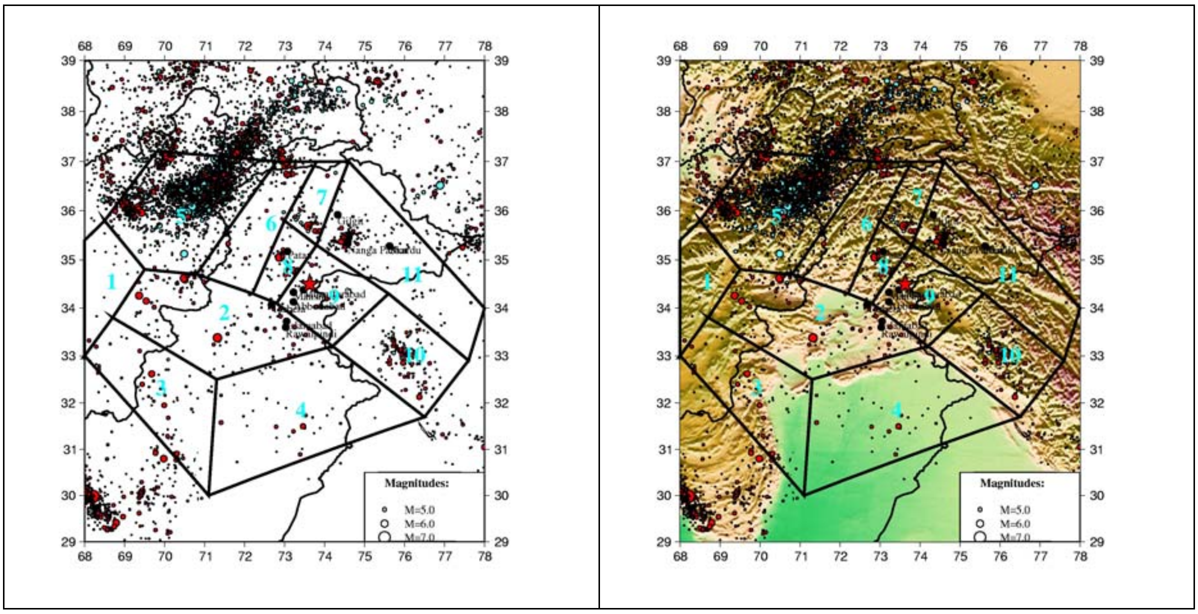


Fig. 5.1. The selected source zones defined in this study based on the above discussion of seismicity and seismotectonics. Note that the two plots are identical except for the relief included in the right basemap.

Zone Number	Region
1	Afghanistan border; the seismicity of this region is low.
2	Bannu area; low seismicity area.
3	Dera Ismail Khan and Dera Ghazi Khan areas; low seismicity.
4	The Jehlum area; seismically active region.
5	Hindukush and Pamir belt; high seismic activity region.
6	Peshawar area; moderate seismicity zone.
7	Chilas area; moderate to high seismic activity.
8	Pattan area; high seismicity zone.
9	Muzaffarabad and Hazara division; earthquake prone area.
10	Sialkot; high potential seismic zone.
11	Nanga Parbat and Gilgit; moderate to high seismic activity.

Table 5.1. Short description of the eleven defined zones

5.2. Quantification of the earthquake recurrence

The basic principles for quantification used in this study are in line with best PSHA practice. Firstly the overall recurrence parameters were established, and in particular a stable *b*-value was found. Thereafter, regressions, with fixed *b*-value were done on the datasets pertaining to each of the defined source zones.

5.2.1. Recurrence values for the large zone

The cumulative Gutenberg-Richter relation was computed for the 33 years of PDE data, selecting depths shallower than 50 km and within the spatial window 29-39N and 68-78E with results shown in Fig. 5.2.

The obtained activity relation was

$$\log(N)=6.23 - 1.09*M$$

This relation was obtained with a regression coefficient of 0.98.

The cumulative Gutenberg-Richter relation was also computed for the depths deeper than 70 km with results shown in Fig. 5.3.

The obtained activity relation was

$$\log(N)=5.69 - 0.95*M$$

This relation was obtained with a regression coefficient of 0.99.

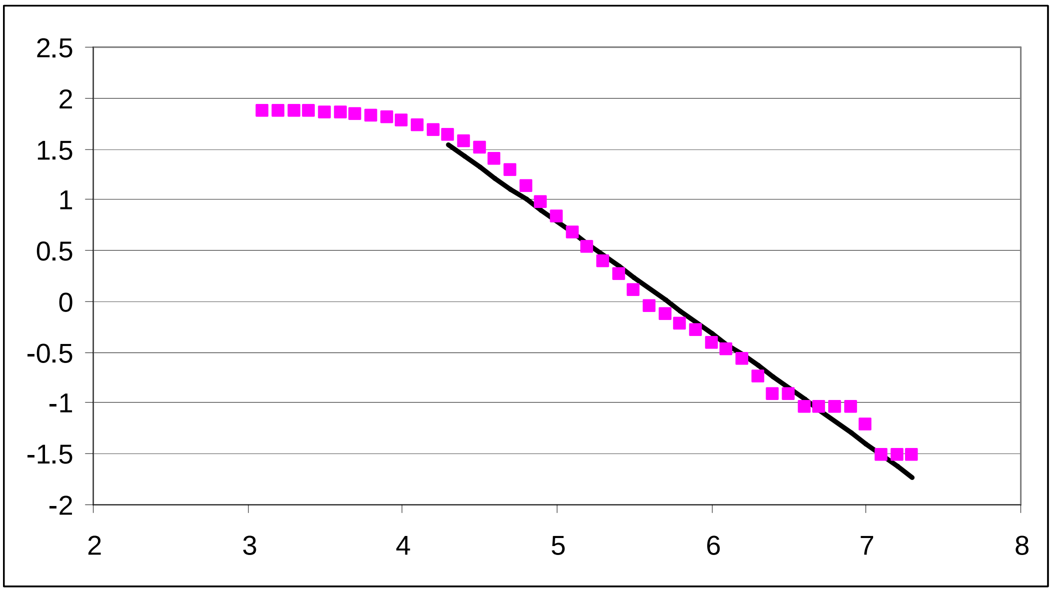


Fig. 5.2. PDE data was collected for the region 29-39N and 68-78E and with depths shallower than 50 km. The cumulative, normalized Gutenberg Richter relation with the regression line log(N)=6.23 – 1.09*M.

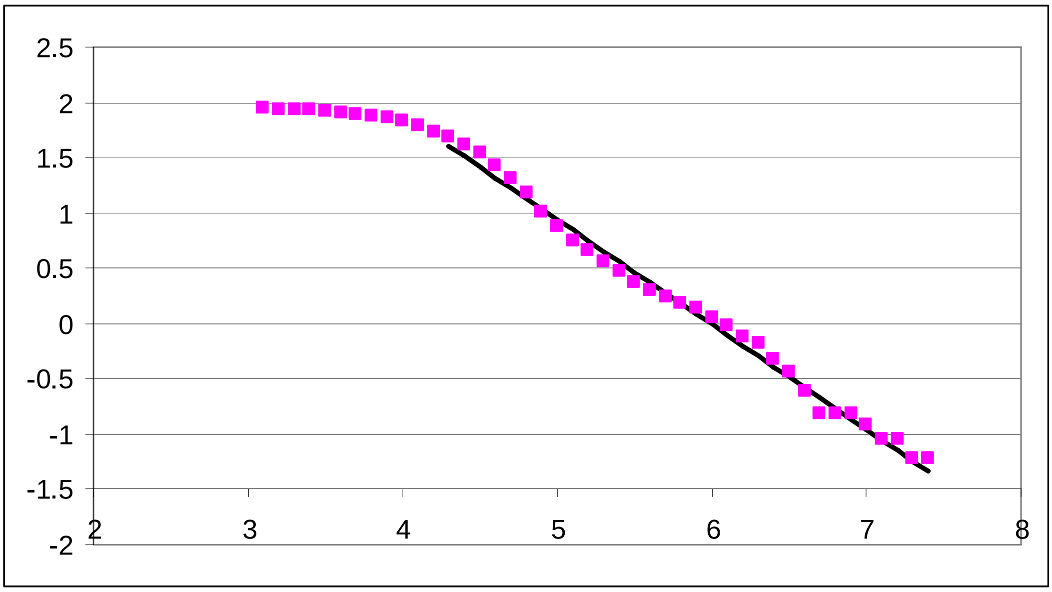


Fig. 5.3. PDE data was collected for the region 29-39N and 68-78E and with depths deeper than 70 km. The cumulative, normalized Gutenberg Richter relation with the regression line log(N)=5.69 – 0.95*M.

5.2.2. Recurrence values for the smaller sub zones

Table 5.2 summarizes the regression parameters found for the eleven subzones defined. The maximum magnitudes observed in the PDE catalog in each zone were augmented with maximum magnitude observations from other sources (and are shown in parentheses when they are larger than the PDE magnitudes).

Zone number	*b*-value	*a*-value	Number of events	Max. observed magnitude (M_{max} reported in other catalogs)
1	1.09	3.59 (±1.07)	7	5.1
2	1.09	5.19 (±0.23)	121	6.3 (6.8 PMD)
3	1.09	4.87 (±0.25)	61	6.3
4	1.09	4.42 (±0.43)	38	5.4 (6.0 PMD)
5	1.09	5.69 (±0.33)	743	7.0 (7.6 EHB)
6	1.09	4.92 (±0.24)	72	6.0 (6.1 PMD)
7	1.09	4.74 (±0.43)	34	6.2 (6.8 EHB)
8	1.09	4.80 (±0.38)	40	6.2 (6.2 PMD)
9	1.09	4.47 (±0.52)	34	5.2 (M=7.6 2005)
10	1.09	5.02 (±0.62)	102	5.5 (8.0 Kangra, 1905)
11	1.09	5.03 (±0.32)	154	6.5

Table 5.2. The activity values (*a*-value) found by regressions on each of the sub-zones together with the maximum observed magnitudes. Note that regressions were done by keeping the *b*-value fixed to the globally found 1.09.

5.2.3. Maximum magnitude for each zone

The maximum magnitudes for the model zones were defined through i) the observed maximum magnitude and ii) the evaluated tectonic potential. Whichever largest magnitude indicated was used in the model, albeit, weighted. The maximum magnitudes observed in Table 5.2 can be compared with the ones used in the computational model as given in Table 7.1.

6. Ground Motion Models

It is well known from many earlier studies that the uncertainties in the wave attenuation models usually contribute significantly to the total uncertainty in the seismic hazard estimates, and this is in particular the case for intraplate areas where local strong motion data are often rare. The most important factor here is the aleatory uncertainty, since the hazard computations integrate directly over the distribution described by the scatter (sigma value) in the ground motion model. The scatter may therefore be as important as the mean with respect to contribution to the total hazard.

In addition to the aleatory uncertainty there is also an epistemic uncertainty that expresses our lack of knowledge. In PSHA models this is taken care of through the use of logic trees where branching is done over a set of ground motion models, with different weights.

6.1. Review of ground motion models

One complicating factor is that we need spectral attenuation relations, i.e., PSV relations for a suit of frequencies. Such relations are much fewer than PGA relations, but even for PGA there are no relations for the Himalaya region.

There are PSV relations available for:

- Transcurrent or strike-slip regimes (e.g., Boore et al., 1997), in particular California where strong motion data, including in the near field, are in abundance compared to any other region in the world. Such regions include also important compressional conditions (revealed for example in hidden thrusts), as seen in many of the recent larger earthquakes (such as 1989 Loma Prieta and 1994 Northridge).

- Subduction zones, including Cascadia, Japan, Mexico and Central America (Crouse, 1991; Climent et al., 1994; Dahle et al., 1994; Atkinson and Boore, 1997). Related to this are also relations for back-arc conditions or volcanic chain and shallow crustal events (Schmidt et al., 1997), where there is an important component of compression, but under crustal conditions which are quite different from the Himalayas.
- Extensional regimes, developing global relations based on data from events revealing normal faulting (Spudich et al., 1997). In terms of stress, this is the quite different from what is found in Himalaya, which by the way may not mean that the relations are very different.
- Intraplate regions (e.g., NORSAR and Risk Engineering, 1991; Atkinson and Boore, 1995; Toro et al., 1997), where the conditions are quite different and where relations, because of insufficient empirical data, moreover have to be based more on simulations and theoretical models.
- Compressional tectonics, where nothing as mentioned is available for the Himalayan region, and where the closest we get is the Mediterranean region (Caillot and Bard, 1993; Ambraseys et al., 1996). Tectonic conditions there are admittedly different, but still reasonably close to be good candidates.

The relations discussed above have been studied in detail at NORSAR, finding that there are some times as much differences between relations assumed to cover the same region as there are differences between tectonically different regions. There is usually no such thing as a ‘best relation’, demonstrating that the epistemic uncertainty is an important factor to be accounted for, as done through the logic-tree methodology.

There are few relations available that have been developed specifically for the Himalayan region, and hardly for any region which is reasonable similar tectonically. Notable exceptions here are the PGA relations by Sharma (1998) and Jain et al. (2000) together with Khademi et al (2002). These PGA relations are together with the one by Ambraseys et al. (1996) among the possible relations, based on the fact that there is some compressional tectonics also in the regions where the Ambraseys data comes from.

6.1.1. Comparisons of selected ground motion models

The following ground motion models were tested for.

1. Ambraseys at el. (1996). Based on 422 horizontal records in the magnitude range 4.0 to 7.9 and distance range 0 – 260 km.
2. Sharma (1998). Based on 41 hard rock records and 25 soil records with distances greater than 50 km. No separation between soil and rock site.
3. Jain et al. (2000). Based on combined SMA and SRR (very simple 3 frequency maximum acceleration measurement device) data. The lowest frequency is 0.4 seconds. Data from Magnitude 5.5 – 7.0 and distance range 0 – 322 km.
4. Khademi et al (2002). Based on 160 horizontal records in the magnitude range 3.4-7.4 in the distance range from 0.1 - 180 km.

These four relations are plotted below in Fig. 6.1. The Sharma and Jain attenuation relations have the advantage of being developed from Himalayan data. With respect to the Jain relation, it is largely based on data from SRR sensors, and sources are not confined to the Himalaya region. With the large difference between the PGA frequency and the highest frequency of the SRR sensors it was decided that the Jain relation was not suitable for the present study. The Sharma relation is based on data obtained both on hard rock and soil sites, however, without distinguishing these different site conditions in the regioression parameters. For this reason, and for the unrealistic low PGA values predicted also the Sharma relation was not used.

The Khademi relation (Fig. 6.1) is based on data from a presumably compressional regime (not specified regions in Iran), and demonstrate unexpected low attenuation. The predicted accelerations from this relation are extremely high at all magnitudes and distances, indicating also a very low scaling with increasing magnitude. While this observation calls for caution, so does also the attenuation form of Khademi which is doubly exponential:

$$PGA = (C_1 e^{C_2 M})(R + C_3 e^{C_4 M})^{C_5}$$

where $C_{1\text{-}5}$ are regression constants and M is magnitude (unknown type) and R is distance.

With the given uncertainty it was decided to use the Ambraseys attenuation relation with varying sigma values of 0.45, 0.50 and 0.60. These scatter values are somewhat conservative.

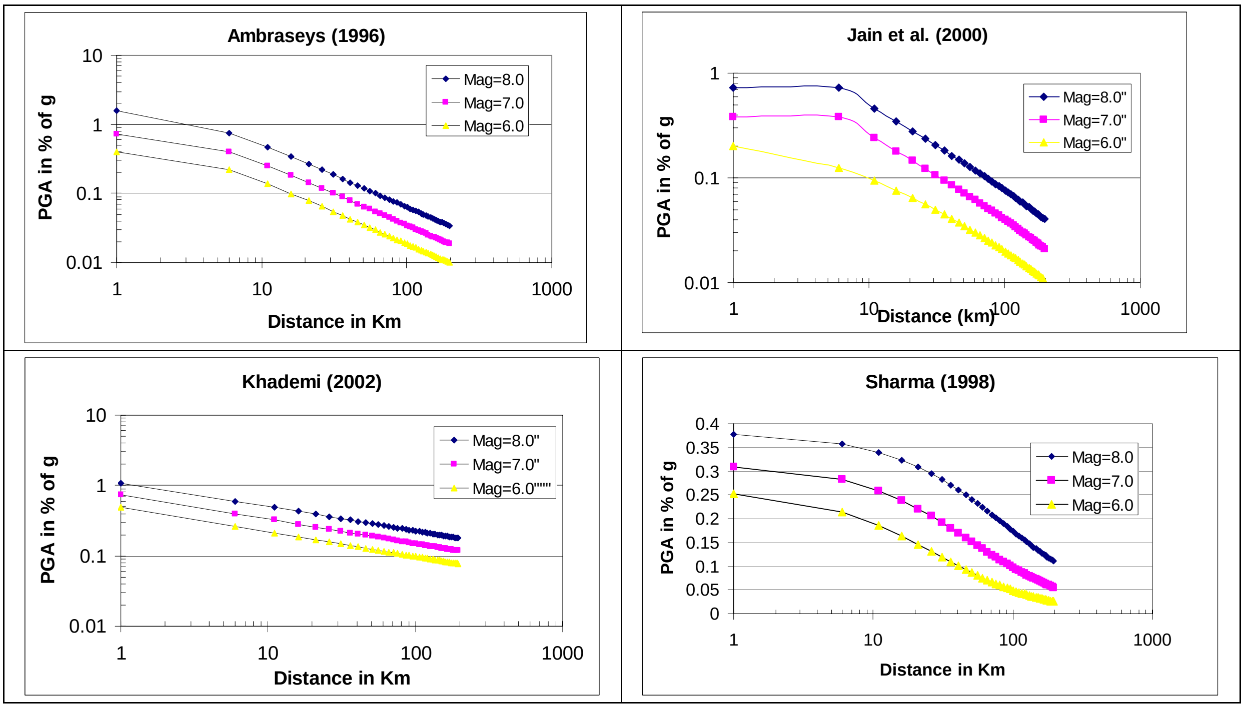


Fig. 6.1. Attenuation relations considered in this study. All relations are collected from the comprehensive worldwide compilation of attenuation relations by Douglas (2004).

7. Computational Model

7.1.1. Area model

The *b*-value of 1.09, which was found with good correlation to the shallow earthquakes, was used globally on all the shallow seismicity in the zones. However, there is an inherent uncertainty with all the seismic activity parameters, and for the *b*-values it was incorporated a spread around the global regression result with values of: 0.85 (0.25) 1.09 (0.50) 1.15 (0.25); Weights in parenthesis.

The maximum magnitude values as shown in Table 7.1 were based on an evaluation of the tectonic capacity and the observed maximum magnitude earthquakes in any of the catalogs at hand.

Zone number	N-values ($M_{threshold}$=4.5) (Faults: $M_{threshold}$=5.5)	M_{max} Weights: 0.25–0.50–0.25
1	0.00412098 0.0484172 0.568853	6.30 6.50 7.00
2	1.13501 1.92752 3.27341	6.80 7.00 7.50
3	0.5188 0.922571 1.64059	6.50 6.70 7.10
4	0.121619 0.327341 0.881049	6.30 6.60 7.00
5	2.85102 6.09537 13.0317	7.80 7.90 8.10
6	0.595662 1.03514 1.79887	7.00 7.40 7.80
7	0.254097 0.683912 1.84077	7.50 7.70 8.00
8	0.327341 0.785236 1.88365	7.50 7.80 8.20
9	0.110917 0.367282 1.21619	7.80 8.00 8.30
10	0.312608 1.30317 5.4325	8.00 8.10 8.30
11	0.638263 1.33352 2.78612	7.30 7.60 8.00
Fault 1	0.645E-03 0.125E-02 0.254E-02	6.80
Fault 2	0.105E-02 0.205E-02 0.455E-02	7.50

Table 7.1. Source and fault modeling parameters used in the PGA computation.

7.1.2. Fault model

The Jehlum fault was modeled in two segments, although it is stressed that the degree of activity is presently unknown, and the subject of future investigations. Nakata et al. (1991) reports that the fault dislocates Pleistocene river terraces, and while a N-S strike-slip fault is expected, WNW-ESE and ENE-WSW trends were found. The results of new investigations of the seismic potential of the Jehlum fault may warrant an update of the current investigation.

The seismic activity was computed by using a moment slip relationship as described in Bungum (2006), using a slip rate of 2 mm/year. The slip rate is presently unknown, but estimated to be between 0 and 3 mm/year (uncertain estimate), so the used 2 mm/year is not represent a very conservative estimate. Two segments were defined, a northern and a southern part reflecting on the observed bend in the fault trace (Fig. 3.1). Table 7.2 provides the fault model coordinates.

For both fault segments the M_{min} was set to 5.5 and the M_{max} value was determined from the fault lengths. As the fault has no recent earthquake activity a low *b*-value of 0.6 was used. This is in line with probabilistic fault modeling, where the low b-value indicates a magnitude distribution more similar to “characteristic” recurrence models (each fault generates only the same size, 'characteristic', earthquakes, governed by the fault size).

For the fault modeling the *N*-values were estimated through the Bungum (2006) procedure, and were based on average of Anderson and Luco (1983) and Youngs and Coppersmith (1985) models relating activity and slip rates. For the relation between area and magnitude the relation reading log(A)=-4.15+M by Wyss (1979) was used.

Northern segment	73.300 34.700 73.500 34.500 73.250 34.300
Southern segement	73.400 34.500 73.600 34.060 73.600 33.700 73.750 33.450

Table 7.2. Coordinates of the two-segment model for the Jehlum fault.

8. Earthquake Hazard Results

Peak Ground Accelerations were computed in a grid of 20 points covering Islamabad and Rawalpindi in the region 72.95-73.07E and 33.58-33.74N comparing to a quadrant of approximately 13x18 km. The results are provided for hard rock conditions and the variation within this area for the 0.002 annual exceedance probability varies between 1.83082 to 2.02107 m/ss as tabulated in Table 8.1. The average PGA value is 1.9 m/ss, and the variation over the grid is regarded as relatively low, justifying to use one hazard curve to be representative for Islamabad and Rawalpindi. (Note, however that this uniformity is valid only for hard rock outcrops).

The hazard curve for hard rock is provided in Figure 8.1 and is tabulated in Table 8.2, indicating that for a return period of 500 years (0.002 annual exceedance probability) the expected ground motion is 1.9 m/ss corresponding to 0.19 g.

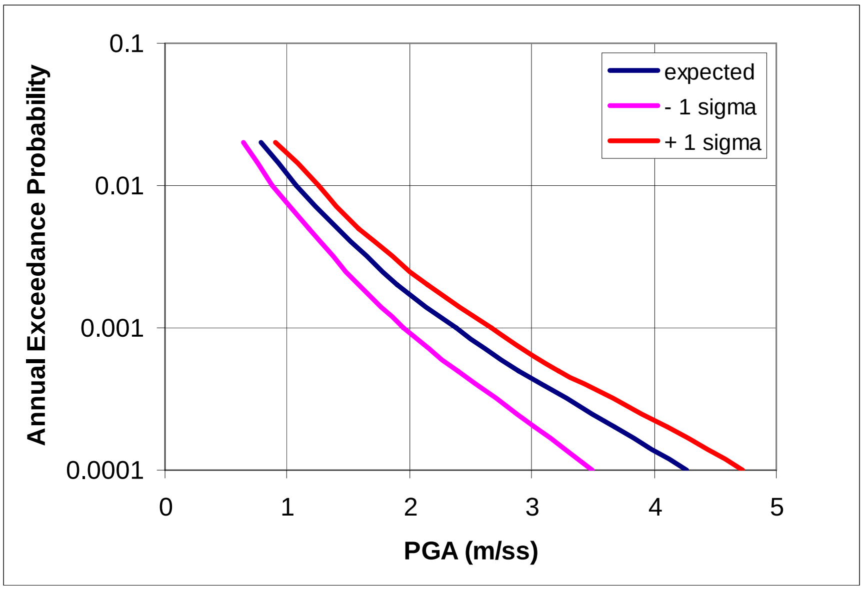


Fig. 8.1. Seismic hazard curve for the site 73.03E and 33.62N.

Longitude	Latitude	PGA (m/ss)	Longitude	Latitude	PGA (m/ss)
72.95	33.58	1.83082	73.03	33.66	1.85284
72.99	33.58	1.84997	73.07	33.66	1.86451
73.03	33.58	1.9125	72.95	33.7	1.86586
73.07	33.58	2.02107	72.99	33.7	1.8782
72.95	33.62	2.01857	73.03	33.7	1.88504
72.99	33.62	1.99904	73.07	33.7	1.89073
73.03	33.62	1.90162	72.95	33.74	1.89244
73.07	33.62	1.84895	72.99	33.74	1.89554
72.95	33.66	1.85712	73.03	33.74	1.89422
72.99	33.66	1.8417	73.07	33.74	1.89991

Table 8.1. Ground motion values (PGA in m/ss) for the 0.002 annual exceedence probability for the sites in the grid.

Annual Exceedence probability	Return period (years)	Expected value	Expected -1 σ	Expected +1σ
0.02	50	0.78611	0.64651	0.90545
0.01	100	1.07741	0.87129	1.25299
0.005	200	1.41609	1.17422	1.58578
0.002	500	1.90122	1.58423	2.14718
0.001	1000	2.37584	1.94753	2.67377
0.0005	2000	2.88964	2.39413	3.22235
0.0002	5000	3.67634	3.02297	4.10516

Table 8.2. Ground motion values (PGA in m/ss) for different annual exceedence probabilities for the site 73.03E and 33.62N. The light shaded row corresponds to the annual exceedance probability most frequently used. The shaded column is the expected ground motion.

8.1. Discussion of the results in view of historical earthquakes

Fig. 4.2 shows that three earthquakes in pre-instrumental times occurred quite close to Rawalpindi. If these reports are reliable, and if these earthquakes were damaging, this may undermine the credibility of the obtained PSHA results. In an attempt to highlight this problem we list some key arguments below:

- It proved not possible to identify more information on the earthquakes than what is tabulated in Table 4.1.
- Rawalpindi is a cultural centre with a close to 2000 year history. As the main regional centre, this is the place where records of unexpected events would be expected made.
    - A corollary of this observation is that any earthquake that is recorded as felt in Rawalpindi not necessary would have its epicenter in Rawalpindi.
    - Another corollary is that observations of how an earthquake was felt would have a tendency to focus on how it was felt in Rawalpindi.
- It is notable that no damaging earthquake is reported from the Rawalpindi region between 25 A.D. and 1969.

The 25 A.D. Taxila earthquake is a very important record, since it is claimed to have left much of the Buddhist culture at that time in ruins. Although no clear conclusions can be drawn from this event we should keep the record in mind. The 1669 Mandra earthquake is located at some distance as is also the Murree Hills earthquake of 1852, so this leaves us with the 1869 Rawalpindi earthquake as a challenge to our PGA results. To this earthquake we may note the following points:

- The maximum intensity is assigned VII to VIII. When such intensities are compared with the descriptions in Appendix 1, there are some discrepancies:
    - From intensity VII it is expected considerable damage to poorly designed structures (as one should expect were abundant in Rawalpindi at the time).
    - At such damages one should expect quite some casualties from a city like Rawalpindi.
    - Contrary to the above intensity descriptions it is only mentioned some cracks in walls in many houses in Rawalpindi.
- The above leads us to believe that the intensity assignment to this earthquake is exaggerated.
- Even some 150 years back it could happen that epicenter definition could be mixed with where the earthquake shaking was strongly recorded. We can therefore not preclude the possibility of this earthquake having its epicenter at considerable distance, but being felt strongly in the regional population centre.

As a final point it is pointed to the fact that thick sediments underlie Rawalpindi, and these sediments will lead to an amplification of the seismic shaking. With a shaking amplification factor of 1.5 for PGA (see below) the 0.18 g bedrock PGA amplifies to 0.27 at the surface. This may be compared with the Intensity – PGA relations listed in Appendix 1.

In conclusion we feel that the 1869 earthquake observations are not solid enough to challenge the obtained results. However, we will at the same time emphasize that there is always uncertainty connected to predicted ground motion estimation.

9. Considerations on soil amplification

The selection of design criteria for any structure is the sole responsibility of the constructor.

Thick soil layers may greatly amplify the ground shaking from an earthquake. Such amplification depends on the soil thickness, consistency and the amplitude and frequency content of the base rock shaking. The detailed characterization of soil amplification is outside the scope of the present study; however, a brief discussion is included below so as to raise awareness for the problem.

The cities of Islamabad and Rawalpindi are underlain by partly thick soil deposits. Fig. 9.1 shows that large parts of the two cities are covered by 5-10 meters of recent to sub-recent alluvium deposits mainly consisting of clays with sand and semi-consolidated gravels. The thickness of the deposits is wedge shaped, thickening to the south.

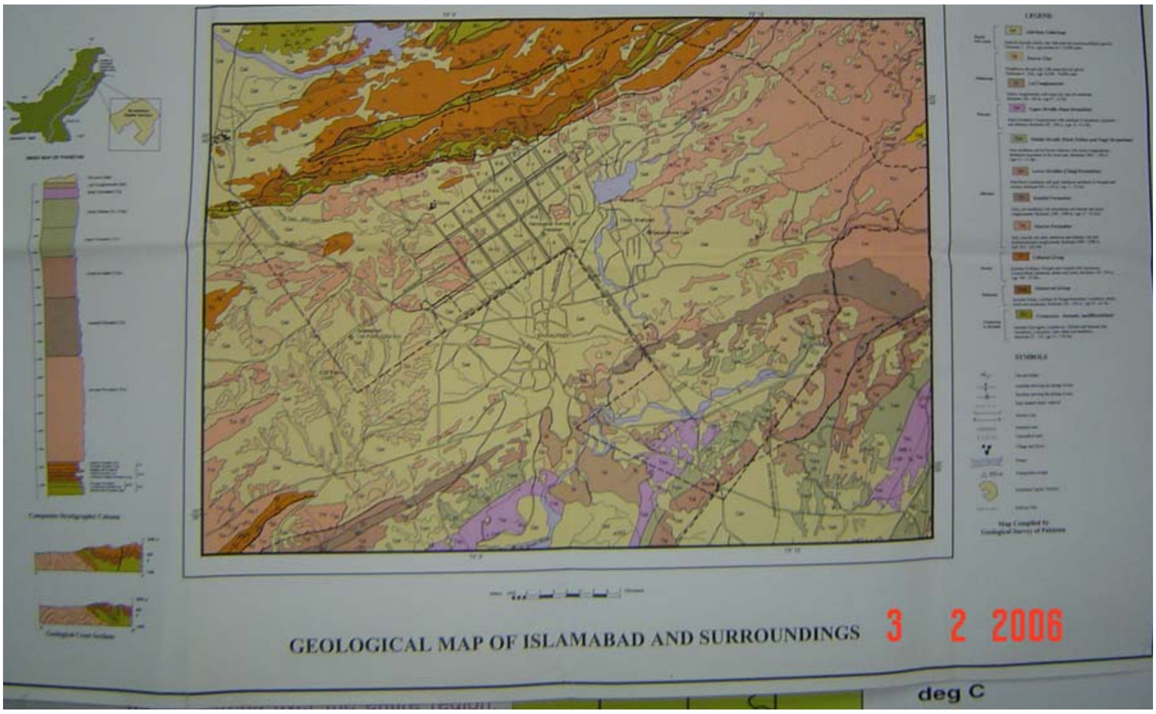


Fig. 9.1. Geological map of Islamabad and Rawalpindi areas compiled by the Geological Survey of Pakistan. Undated map.

For the soil profiles shown in Table 9.1, the soil amplification factors were computed as shown in Table 9.2.

Bore hole No.	Depth (ft)	Unconfined compressive strength (qu) T/S ft)	Allowable bearing Capacity (qa) (T/S ft)
1	05	1.40	1.40
	10	1.30	1.30
	15	1.33	1.33
	20	2.56	2.56
2	05	1.67	1.67
	10	1.25	1.25
	15	1.32	1.32
	20	1.03	1.03

Table 9.1a. Soil description from two boreholes in Islamabad.

B.H. No.	Depth (ft)	Grain Size Analysis				Symbol			Description
		Gravel	Sand	Silt	Clay	L.L	P.L	P.I	
1	10	01	07	85	07	29.99	22.45	7.54	Silt, brown colour, medium plasticity, inorganic.
	20	00	03	89	08	35.59	27.77	7.89	Silt, brown colour, medium plasticity, inorganic.
	30	00	05	88	07	28.98	21.67	7.38	Silt, brown colour, medium plasticity, inorganic.
2	05	00	05	87	08	30.33	22.45	7.88	Silt, brown colour, medium plasticity, inorganic.
	15	00	04	88	08	34.80	25.96	8.84	Silt, brown colour, medium plasticity, inorganic.
	25	01	04	88	07	29.86	22.47	7.59	Silt, brown colour, medium plasticity, inorganic.

Table 9.1b. Soil description from two boreholes in Islamabad

T	Weak (0.1g)
(sec)	Amplification
0	2.5
0.4	2.5
0.7	3.5
10	3.5

T	Weak (0.25g)
(sec)	Amplification
0	1.5
0.4	1.5
1	3
10	3

T	Strong (0.4g)
(sec)	Amplification
0	0.9
0.4	0.9
1.5	2.4
10	2.4

Table 9.2. Amplification factors estimated for the soil profiles of Islamabad and Rawalpindi. Factors developed by Dr. A. Kaynia for this project. Linear interpolation is recommended for periods not covered above. Note: A period of 0 Seconds is taken as the PGA frequency.

For the intermediate PGA values (around 0.25 g) the amplification factor 1.5 is recommended for PGA. For comparison: the PGA amplification factor recommended in the Norwegian construction standard for somewhat stiffer soil profiles is 2.25 (Dr. A. Kaynia, pers. communication).

These values may also be compared with two UBC spectra developed for Hard Rock sites and soil type C (very dense soil and soft rock with Vs velocities in the range 360-760 m/s). The main message in Fig. 9.2 in the present context is the significant amplification factor on higher periods, and the shift of the higher "corner" period.

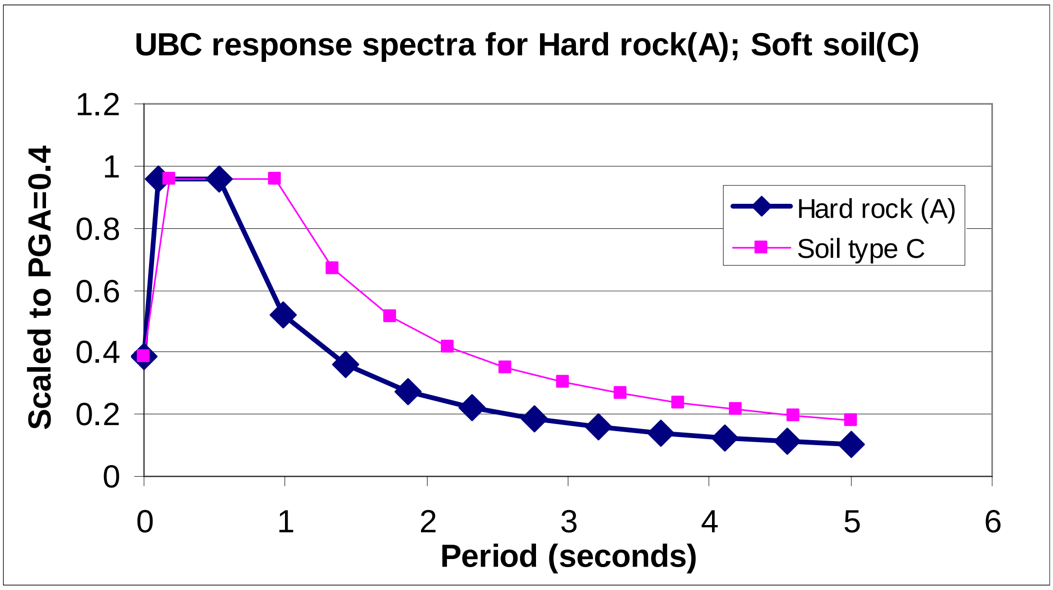


Fig. 9.2. UBC design spectra for hard rock and soil type C.

10. Design spectra

It is outside the scope of this work to recommend design spectra. One may, however, compute response spectra based on the UBC code and adapted to the PGA values found above.

When this is done and shown in Fig. 10.1 below it is stressed that this is an example, and more detailed engineering considerations than here is necessary for confirming appropriate design spectra.

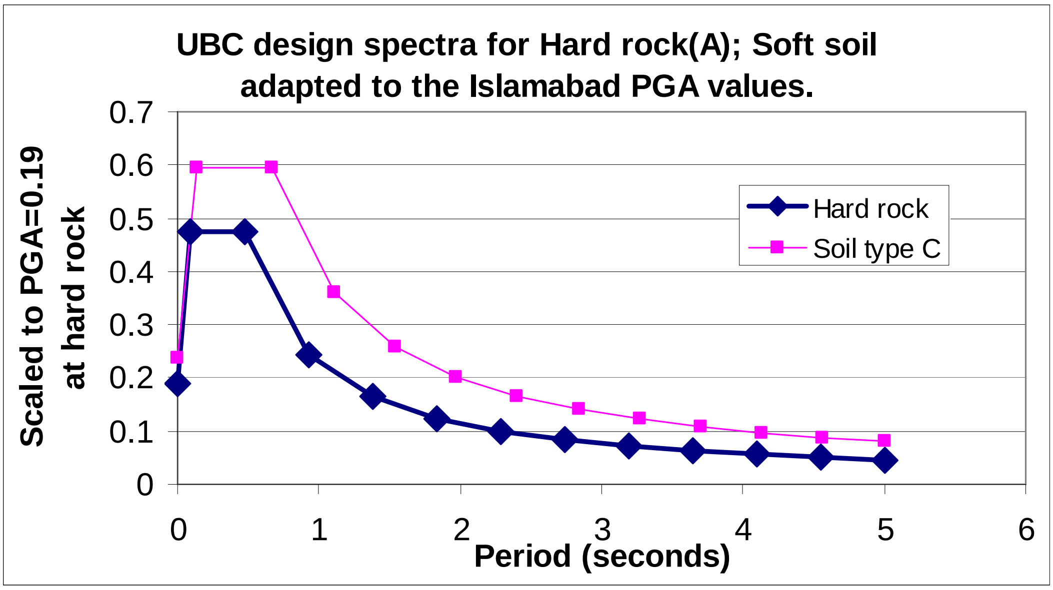


Fig. 10.1. UBC design spectrum tentatively adapted to the PGA values found for Islamabad and Rawalpindi above.

11. References

Ambraseys N., G. Lensen and M. Moinfar (1975): The Pattan earthquake of 28 Dec., 1974. Reconnaissance report prepared for the Government of Pakistan y UNESCO.

Ambraseys, N.N., K.A. Simpson and J.J. Bommer (1996): Prediction of horizontal response spectra in Europe. *Earth. Eng. Struct. Dyn*., 25, 371-400.

Anderson, J.G. and J.E. Luco (1983): Consequences of slip rate constants on earthquake occurrence relations. Bull. Seism. Soc. Am., 73, 471-496.

Atkinson, G.M. and D.M. Boore (1995): Ground-motion relations for Eastern North America. *Bull. Seism. Soc. Am*., 85, 17-30.

Atkinson, G.M. and D.M. Boore (1997): Some comparisons between recent groundmotion relations. *Seism. Res. Lett*., 68, 24-40.

Bilham R., V. Gaur and P. Molnar (2001): Himalayan seismic hazard. *Science*, 293, 2001.

Boore, D.M., W.B. Joyner and T.E. Fumal (1997): Equations for estimating horizontal response spectra and peak accelerations from western North American earthquakes: A summary of recent work. *Seism. Res. Lett*., 68, 128-153.

Bungum H. (2006): Numerical modeling of fault activities. Submitted to Computer and Geosciences.

Caillot, V. and P.-Y. Bard (1993): Magnitude, distance and site dependent spectra from Italian accelerometric data. *Europ. Earthq. Eng*., 1, 37-48.

Climent, A., W. Taylor, M. Ciudad Real, W. Strauch, M. Villagran, A. Dahle and H. Bungum (1994): Spectral strong motion attenuation in Central America. NORSAR Technical Report No. 2-17 under the project "Reduction of Natural Disasters in Central America". NORSAR, Kjeller, Norway.

Cornell, C.A. (1968): Engineering seismic risk analysis. *Bull. Seism. Soc. Am*., 58,1583 1606.

Crouse, C.B. (1991): Ground-motion attenuation equations for earthquakes on the Cascadia subduction zone. *Earthq. Spectra*, 7, 201-236.

Dahle, A., A. Climent, W. Taylor, H. Bungum, P. Santos, M. Ciudad-Real, C. Lindholm, W. Strauch and F. Segura (1995): New spectral strong-motion attenuation models for Central America. *Proc., 5th Int. Conf. on Seismic Zonation*, Vol. II, pp. 1005-1012.

Der Kiureghian, A. and A.H.-S. Ang (1977): A fault rupture model for seismic risk analysis. *Bull. Seism. Soc. Am*., 67, 1173-1194.

Douglas J. (2004): Ground estimation equations 1964-2003; A comprehensive worldwide summary of strong-motion attenuation relationships for peak ground acceleration and spectral ordinates (1969 to 2000) with corrections and additions. Imperial College. Research report No. 04-001-SM

Jain S.K., A. Roshan, J. Arlekar and P. Basu (2000): Empirical attenuation relationships for the Himalayan earthquakes based on Indian strong motion data. In: Proceedings of the sixth International Conference on seismic Zonation.

Khademi M. H. (2002): Attenuation of peak and spectral accelerations in the Persian Platau. In: Proceedings of the Twelfth European Conf. on Earthq. Eng., Paper No. 330.

Kulkarni, R.B., R.R. Young and K.J. Coppersmith (1984): Assessment of confidence intervals for results of seismic hazard analysis. *Proc. Eighth World Conf. on Earthq. Eng., San Francisco*, Vol. 1, pp. 263-270.

Mahdi (2005): Mangla Dam Project. Seismicity Report 2004-2005. Pakistan Water and Power Development Authority.

McGuire, R.K. (1976): FORTRAN computer programs for seismic risk analysis. *U.S. Geol. Survey Open File Report No 76-67*.

McGuire, R.K. (1978): FRISK: Computer program for seismic risk analysis using faults as earthquake sources. *U.S. Geol. Survey Open File Report No 78-1007*.

McGuire, R. (1995): Probabilistic seismic hazard analysis and design earthquakes: closing the loop. *Bull. Seism. Soc. Am.*, 85, 1275-1284.

Mortgat, C.P. and H.C. Shah (1979): A Bayesian model for seismic hazard mapping. *Bull. Seism. Soc. Am.*, 69, 1237-1251.

Nakata T., H. Tsutsumi, S. Hasan Khan and R. Lawrence (1991): Active faults of Pakistan. Research centre for regional geography, Hiroshima University, Japan. Publication No. 21.

NORSAR and Risk Engineering, Inc. (1991): *Ground motions from earthquakes on the Norwegian Continental Shelf*. Report for Operatørkomite Nord (OKN), Stavanger, Norway.

Reiter L. (1990): Earthquake hazard analysis; Issues and insights. Columbia University Press.

Schmidt, V., A. Dahle and H. Bungum (1997): *Costa Rican spectral strong motion attenuation*. Technical Report from the project 'Reduction Natural Disasters in Central America, Phase II', NORSAR, Norway.

Sharma, M.L. (1998): Attenuation relationship for estimation of peak ground horizontal acceleration using data from strong-motion arrays in India. *Bull. Seism. Soc. Am.*, 88, 1063-1069.

Sharma, M. L., (2003): Estimation of spectral strong ground motion using strong motion data from the Himalayas. HIMPROB_2003, Department of Earth Sciences, IIT Roorkee, 82-83.

Spudich, P. et al. (1997): SEA96 - A new predictive relation for earthquake ground motions in extensional tectonic regimes. *Seism. Res. Lett.*, 68, 190-198.

Toro, G.R., N.A. Abrahamson and J.F. Schneider (1997): Model of strong ground motions from earthquakes in Central and Eastern North America: Best estimates and uncertainties. *Seism. Res. Lett*., 68, 41-57.

U.S. Army Corps of Engineers (1999): Response spectra and seeismic analysis for concrete hydraulic structures. Engineers Manual. EM 1110-2-6050

Woo, G. (1985): *PRISK manual*. Principia Mechanica Ltd., London.

Wyss, M. (1979): Estimating maximum expectable magnitude of earthquakes from fault dimensions. Geology, 7, 336-340.

Youngs, R.R. and K. Coppersmith (1985): Implications of fault slip rates and earthquake recurrence models to probabilistic seismic hazard estimates. *Bull. Seism. Soc. Am.*, 75, 939-964.

Zhang P., Z. Yang, H. Gupta, S. Bathia and K. Shedlock (1999): Global Seismic Hazard Assessment Program (GSHAP) in continental Asia. Annali di Geofisica, 42 pp. 1167-1190.

12. Glossary

Accelerogram - Time history of accelerations.

Active fault - (1) A fault that has had sufficiently recent displacements so that, in the opinion of the user of the term, further displacements in the foreseeable future are considered likely. (2) A fault that on the basis of historical, seismological, or geological evidence has a high probability of producing an earthquake. (3) A fault that may produce an earthquake within a specified exposure time, given the assumptions adopted for a specific seismic-risk analysis.

Attenuation - The reduction in amplitude of a wave with time or distance traveled, most often used for the decrease in amplitude of ground motion with increase in distance from the source. This attenuation is due to two mechanisms, one is the distribution of energy over a larger volume as the distance increases, the other is the loss of energy due to internal damping. The latter effect is frequency dependent and gives higher attenuation of the high frequency motion.

Attenuation law - A description of the behavior of a characteristic of earthquake ground motion as a function of the distance from the source of energy.

B-value - A parameter indicating the relative frequency of earthquakes of different sizes. It is the slope of a straight line indicating absolute or relative frequency (plotted logarithmically) versus earthquake magnitude (or meizoseismal intensity), often shown to be stable over a wide range of magnitudes. The B-value indicates the slope of the curve of the Gutenberg-Richter recurrence relationship.

Body waves - A seismic wave that travels through the interior of an elastic material. These waves consist of compressional waves (P-waves) and shear waves (S-waves). Near the source most of the energy carried is in the form of body waves.

Capable fault - A fault along which it is mechanically feasible for sudden slip to occur. Evaluation of capability is based on geologic and/or seismic evidence. Capable is used for faults where it is possible, but not certain, that earthquakes can occur, often used synonymously with potentially active faults.

Continental plate - A large rigid part of the earth's crust and upper mantle (lithosphere) which moves relative to the other continental plates. The speed of movement may be up to 15-20 cm/year. Scandinavia belongs to the Eurasian continental plate.

Crust - The outer major layer of the earth, separated from the underlying mantle by the Moho discontinuity, and characterized by P-wave velocity less than 8 km/s. The thickness of the crust in the Norwegian Continental Shelf in the range 15-25 km.

Damping - Loss of energy in wave motion due to transfer into heat by frictional forces. In engineering often expressed relative to the critical damping, C_{cr} = 2*sqrt(KM), where K and M are stiffness and mass of the vibrating system, respectively.

Design acceleration - A specification of the ground acceleration at a site in terms of a single value such as the peak or rms; used for the earthquake-resistant design of a structure (or as a base for deriving a design spectrum). See **Design time history**.

Design earthquake - (1) A specification of a seismic ground motion at a site; used for the earthquake-resistant design of a structure. (2) An earthquake event used the earthquake-resistant design of structures, which may or may not be equivalent to the maximum earthquake prescribed for the installation.

Design event (Design seismic event) - A specification of one or more earthquake source parameters, and of the location of energy release with respect to the site of interest; used for the earthquake-resistant design of structures.

Design ground motion - Description of ground shaking (e.g., time history, response spectrum) at a given site used for the earthquake-resistant design of structures; in modern hazard studies usually the result of contributions from all seismic sources surrounding the site and not corresponding to any specific design earthquake. See **Design earthquake**.

Design spectrum - A set of curves for design purposes that gives acceleration, velocity or displacement (usually absolute acceleration, relative velocity, and relative displacement of the vibrating mass) as a function of period of vibration and damping.

Deterministic hazard assessment - An assessment that specifies single-valued parameters such as maximum earthquake magnitude or peak ground acceleration without consideration of likelihood.

Duration - A qualitative or quantitative description of the length of time during which ground motion at a site shows certain characteristics (perceptibility, violent shaking, etc.).

Earthquake - A sudden motion or vibration in the earth caused by the abrupt release of energy in the earth's lithosphere; shaking of the ground by different types of waves generated by tectonic movements or volcanic activity. By far the largest number of destructive earthquakes are caused by tectonic movements. An earthquake is initiated when the accumulated tectonic stresses at any one point in the ground become greater than the strength at this point. Release of stress at one point may increase the stresses nearby, and result in a progressive rupture which may propagate for several hundred kilometers. The rupture will almost invariably occur along old zones of weakness (faults), and the wave motion may range from violent at some locations to imperceptible at others.

Earthquake cycle - For a particular fault, fault segment, or region, a period of time that encompasses an episode of strain accumulation and its subsequent seismic relief.

Epicenter - The point on the earth's surface that is directly above the focus (hypocenter) of an earthquake.

Equal hazard spectrum - Specifies ground motion (usually pseudo-relative velocity) as a function of natural period and damping level for a given probability of occurrence. The term is sometimes used synonymously with design spectrum or response spectrum.

Deterministic hazard assessment - An assessment that specifies single-valued parameters such as maximum earthquake magnitude or peak ground acceleration without consideration of likelihood.

Fault - A fracture or a zone of fractures along which displacement has occurred parallel to the fracture. Earthquakes are caused by a sudden rupture along a fault or fault system; the ruptured area may be up to several thousand square kilometers. Relative movements across a fault may typically be tens of centimeters for magnitude 6.0-6.5 earthquakes, several meters for magnitude 7-8 earthquakes.

Fault slip rate - The rate of slip on a fault averaged over a time period involving several large earthquakes. The term does not necessarily imply fault creep.

Geologic hazard – A geologic process (e.g., landsliding, soil liquefaction, active faulting) that during an earthquake or other natural events may produce adverse effects n structures.

Hypocenter - The point where the earthquake started, also called focus. Hypocenter depths are typically 30 km and less for shallow earthquakes, several hundreds of kilometers for earthquakes occurring in subduction zones. Most earthquakes in Fennoscandia originate at depths between 10 and 30 km.

Intensity (of an earthquake) - A qualitative or quantitative measure of the severity of ground shaking at a given site (e.g., MSK intensity, Modified Mercalli intensity, Rossi-Forel intensity, Housner Spectral intensity, Arias intensity, peak acceleration, etc.) based on effects of the earthquake such as how the earthquake was felt, damage to structures, how people reacted, soil or rock slides, etc.

Interplate earthquake - An earthquake along a tectonic late boundary. Most earthquakes are caused by the relative plate movements along plate margins, i.e., between plates.

Intraplate earthquake - An earthquake within a tectonic plate. Scandinavia belongs to the Eurasian plate and is well removed from the nearest plate boundary.

Isoseismal - Contour lines drawn to separate one level of seismic intensity from another.

Logic tree - A formalized decision flow path in which decisions are made sequentially at a series of *nodes***,** each of which generates *branches* flowing to subsequent nodes.

Macroseismic - Ground shaking which gives noticeable effects. See **Intensity**.

Magnitude - A measure of earthquake size at its source. Magnitude was defined by C. Richter in 1935 as: "The logarithm to the trace amplitude in 0.001 mm on a standard

Wood-Anderson seismometer located 100 km from the epicenter" The Wood-Anderson instrument measures the responses in the period range near 1 sec. Other magnitude scales have later been devised based on the responses measured in other period ranges, and on maximum amplitudes of specific wave forms Some of the more commonly used magnitude scales are:

1. M_L= local magnitude, similar to the original Richter magnitude. Usually determined from shear wave response in the period range near 1 sec. at relatively close distances from the epicenter (< 600 km).
2. m_b= body wave magnitude is based on the largest amplitude of body waves, usually the compressional component with period near 1 sec.
3. M_S= surface wave magnitude is measured in the period range near 20 sec.
4. M_W=moment magnitude is based on the seismic moment and be computed directly from source parameters or from long period components in the earthquake record. Symbol M is also used for this magnitude.

Magnitude scales are also based on other earthquake parameters such as felt area, length of rupture and surface displacement, and area within different intensity zones.

A large number of empiric relations between magnitude and other earthquake parameters such as energy, fault movement, fault area, intensity, maximum acceleration, etc., are available. Such relations may differ considerably from one seismic region to another.

Maximum credible, expectable, expected, probable - These terms are used to specify the largest value of a variable, for example, the magnitude of an earthquake, that might reasonable be expected to occur. In the view of the

EERI (Earthquake Engineering Research Institute, U.S.) Committee on Seismic Risk (cf. *Earthquake Spectra*, Vol 1, pp. 33-40), these are misleading terms and their use is discouraged.

Maximum credible earthquake - The maximum earthquake that is capable of occurring in a given area or on a given fault during the current tectonic regime; the largest earthquake that can be reasonably expected to occur (USGS); the earthquake that would cause the most severe vibratory ground motion capable of being at the site under the current known tectonic framwork (US Bureau of Reclamation). "Credibility" is in the eyes of the user of the term.

Maximum earthquake - The maximum earthquake that is thought, in the judgement of the user, to be appropriate for consideration in the location and design of a specific facility.

Maximum possible - The largest value possible for a variable. This follows from an explicit assumption that larger values are not possible, or implicitly from assumptions that related variables or functions are limited in range. The maximum possible value may be expressed deterministically or probabilistically.

Maximum probable earthquake - The maximum earthquake that, in the judgement of the user, is likely to occur in a given area or on a given fault during a specific time period in the future.

Mean (average) recurrence interval - The mean (average) time between earthquakes or faulting events with specific characteristics (e.g., magnitude ε5) in a specified region or in a specific fault zone.

Mean (average) return period - The mean (average) time between occurrences of ground motion with specified characteristics (e.g., peak horizontal acceleration ε0.1 g) at a site. Equal to the inverse of the annual probability of exceedance.

Moho - Mohorovicic discontinuity, a sharp discontinuity in seismic velocities separating the earth's crust from the underlying mantle, also called the crust-mantle boundary. P wave speeds are typically 6.7-7.2 km/s in the lower crust and 7.6-8.6 km/s at the top of the upper mantle.

Neotectonics - (1) The study of post-Miocene structures and structural history of the earth's crust. (2) The study of recent deformation of the crust, generally Neogene (post-Oligocene). (3) Tectonic processes now active, taken over the geologic time span during which they have been acting in the presently observed sense, and the resulting structures.

P wave - A seismic body wave with particle motion in the direction of propagation, also called compressional wave even though the motion alternates between extension and compressions.

Potentially active fault - A term used by different people in different ways, but sometimes referring to a fault that has had displacements on it within the late Quaternary period.

Pseudo acceleration (PSA) - See **Response spectrum**.

Pseudo velocity (PSV) - See **Response spectrum**.

Response spectrum - Describe the maximum response of single-degree-of-freedom systems (linear oscillator) to given ground motions (e.g., an earthquake accelerogram) as a function of the period and the damping of the system. The responses may be pseudo acceleration, pseudo velocity or relative displacement. Pseudo acceleration and pseudo velocity values may be expressed in an approximate way from the relative displacement through the relation: where $PSA/\omega^2 = (PSV)/\omega = RD$ is pseudo acceleration, PSV is pseudo velocity and RD relative displacement, respectively, and ω is circular frequency. By using the pseudo values, all three responses can be plotted together in a logarithmic, tripartite nomogram.

Return period - Same as recurrence interval, average time period between earthquakes of a given size in a particular region, cycle time.

S wave - A seismic body wave with particle motion perpendicular to the direction of propagation, also called shear wave. The passage of an S-wave involves a pure shear of the medium.

Secondary effects - Nontectonic surface processes that are directly related to earthquake shaking or to tsunamis.

Seismic activity rate - The mean number per unit time of earthquakes with specific characteristics (e.g., magnitude ε5) originating on a selected fault or in a selected area.

Seismic design load effects - The actions (axial forces, shears, or bending moments) and deformations induced in a structural system due to a specified representation (time history, response spectrum, or base shear) of seismic design motion.

Seismic design loading - The prescribed representation (time history, response spectrum, or equivalent static base shear) of seismic ground motion to be used for the design of a structure.

Seismic event - The abrupt release of energy in the earth's lithosphere, causing an earthquake.

Seismic hazard - Any physical phenomenon or effect (e.g., ground shaking, ground failure, landsliding, liquefaction) associated with an earthquake that may produce adverse effects on human activities, representing the earthquake's potential danger. Specifically, the probability of occurrence over a given time period in a given location of an earthquake with a given level of severity. Seismic exposure may be used synonymously with seismic hazard.

Seismic moment - The area of a fault rupture multiplied by the average slip over the rupture area and multiplied by the shear modulus (rigidity) of the affected rocks. Seismic moment can be determined directly from the long period asymptote of path corrected far field displacement spectra. Dimension dyne-cm or N-m.

Seismic moment rate - The long term rate at which seismic moment is being generated.

Seismic risk - The probability that social or economic consequences of earthquakes will equal or exceed specified values at a site, at several sites, or in an area, during a specified exposure time; the likelihood of human and property loss that can result from the hazards of an earthquake. Often expressed as hazard times vulnerability.

Seismic zone - A generally large area within which seismic design requirements for structures are constant. Some times used synonymously with **Seismogenic zone**.

Seismic zoning (zonation) - The process of determining seismic hazard at many sites for the purpose of delineating seismic zones. Some times used synonymously with **Seismotectonic zoning.**

Seismicity - The occurrence of earthquakes in space and time.

Seismogenic structure - A geologic structure that is capable of producing an earthquake.

Seismogenic zone (province) - A planar representation of a three-dimensional domain in the earth's lithosphere in which earthquakes are inferred to be of similar tectonic origin; may also represent a fault. See **Seismotectonic zone**.

Seismotectonic zone (province) - A seismogenic zone in which the tectonic processes causing earthquakes have been reasonably well identified; usually these zones are fault zones. In seismic hazard analyses often used to describe a region (area) within which the active geologic and seismic processes are considered to be relatively uniform.

Seismotectonics - The study of the tectonic component represented by seismic activity; a subfield of active tectonics concentrating on the seismicity, both instrumental and historical, and dealing with geological and other geophysical aspects of seismicity.

Strain - Change in the shape or volume of a body as a result of stress.

Stress - Force per unit area.

Stress drop - The sudden reduction in stress across the fault plane during rupture. Intraplate earthquakes have in general higher stress drop than interplate earthquakes. Typical values are 1-10 MPa (10-100 bars).

Surface waves - Seismic waves travelling along the surface of the earth or along layers in the earth's crust, with a speed less than that of S waves. The two most common types are Raleigh waves and Love waves.

Tectonics - A branch of geology dealing with the broad architecture of the outer part of the earth, that is, the regional assembling of structural or deformational features, a study of their mutual relations, origin, and historical evolution.

Vulnerability - (1) The degree of loss to a given element at risk, or set of such elements, resulting from an earthquake of a given magnitude or intensity, usually expressed on a scale from 0 (no loss) to 10 (total loss). (2) Degree of damage caused by various levels of loading. The vulnerability may be calculated in a probabilistic or deterministic way for a single structure or groups of structures.

13. Appendix 1; The Modified Mercalli Intensity Scale (MMI)

Scale: Mercalli	Scale: Richter	Description
I	0-4.3	Vibrations are recorded by instruments. People do not feel any Earth movement.
II		People at rest upstairs notice shaking. A few people might notice movement if they are at rest and/or on the upper floors of tall buildings.
III		Shaking felt indoors; hanging objects swing. Many people indoors feel movement. Hanging objects swing back and forth. People outdoors might not realize that an earthquake is occurring.
IV	4.3-4.8	Dishes rattle; standing cars rock; trees shake. Most people indoors feel movement. Hanging objects swing. Dishes, windows, and doors rattle. The earthquake feels like a heavy truck hitting the walls. A few people outdoors may feel movement. Parked cars rock.
V		Doors swing; liquid spills from glasses; sleepers awake. Almost everyone feels movement. Sleeping people are awakened. Doors swing open or close. Dishes are broken. Pictures on the wall move. Small objects move or are turned over. Trees might shake. Liquids might spill out of open containers.
VI	4.8-6.2	People walk unsteadily; windows break; pictures fall off walls. Everyone feels movement. People have trouble walking. Objects fall from shelves. Pictures fall off walls. Furniture moves. Plaster in walls might crack. Trees and bushes shake. Damage is slight in poorly built buildings. No structural damage.
VII		Difficult to stand; plaster, bricks, and tiles fall; large bells ring. People have difficulty standing. Drivers feel their cars shaking. Some furniture breaks. Loose bricks fall from buildings. Damage is slight to moderate in well-built buildings; considerable in poorly built buildings.
VIII	6.2-7.3	Car steering affected; chimneys fall; branches break; cracks in wet ground. Drivers have trouble steering. Houses that are not bolted down might shift on their foundations. Tall structures such as towers and chimneys

		might twist and fall. Well-built buildings suffer slight damage. Poorly built structures suffer severe damage. Tree branches break. Hillsides might crack if the ground is wet. Water levels in wells might change.
IX		General panic; damage to foundations; sand and mud bubble from ground. Well-built buildings suffer considerable damage. Houses that are not bolted down move off their foundations. Some underground pipes are broken. The ground cracks. Reservoirs suffer serious damage.
X		Most buildings destroyed; large landslides; water thrown out of rivers. Most buildings and their foundations are destroyed. Some bridges are destroyed. Dams are seriously damaged. Large landslides occur. Water is thrown on the banks of canals, rivers, lakes. The ground cracks in large areas. Railroad tracks are bent slightly.
XI	7.3-8.9	Railway tracks bend; roads break up; large cracks appear in ground; rocks fall. Most buildings collapse. Some bridges are destroyed. Large cracks appear in the ground. Underground pipelines are destroyed. Railroad tracks are badly bent.
XII		Total destruction; "waves" seen on ground surface; river courses altered; vision distorted. Almost everything is destroyed. Objects are thrown into the air. The ground moves in waves or ripples. Large amounts of rock may move.

The description above is an abbreviated version which can be found on the Internet.

Relating Intensities and PGA

The question of relating instrumental, quantitative ground shaking with intensity is very important, but also difficult and uncertain. The latest contribution to this issue was provided by Kaka and Atkinson (2004). They compared ground motion in terms of PGV and PSA with intensities for 18 earthquakes in eastern north America.

In line with earlier authors (e.g. Wald et al., 1999) they conclude that intensity correlates better with velocity than with acceleration, however, they also contend that the results for eastern America are significantly different from results obtained for California (Boatwright et al., 2001; Wald et al., 1999).

The Table and Figure below are collected from the homepage of Dave Wald and is indicative of relations between ground motion and intensity:

Intensity	I	II-III	IV	V	VI	VII	VIII	IX	X+
Peak Accel. (% g)	<0.17	0.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
Peak Velocity (cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116

Table 1: Ranges of Ground Motions for Modified Mercalli Intensities

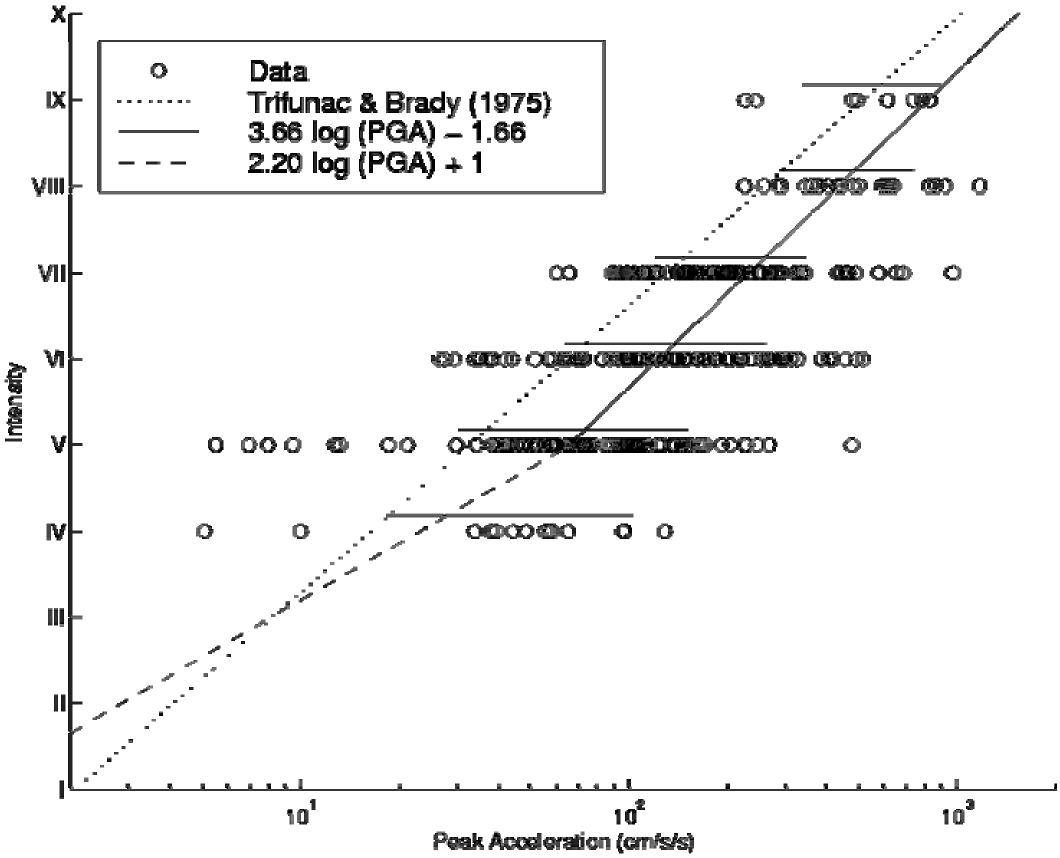


Figure 1: Modified Mercalli intensity plotted against peak ground acceleration for all events combined. Circles denote data; horizontal lines above data depict the range of the geometric mean, plus and minus one standard deviation. The solid line is regression from this study, the dashed line is assigned (see text for details).

References:

Kaka SanLinn I.and Gail M. Atkinson (2004): Relationships between Instrumenta Ground-Motion Parameters and Modified Mercalli Intensity in Eastern North America. Bull. Seism. Soc. Am., 95, pp. 1728–1736,

Wald, D. J., V. Quitoriano, T. H. Heaton, and H. Kanamori (1999a). Relationships between peak ground acceleration, peak ground velocity, and modified Mercalli intensity in California, Earthquake Spectra 15, 557–564.

Boatwright, J., K. Thywissen, and L. Seekins (2001). Correlation of ground motion and intensity for the 17 January 1994 Northridge, California, earthquake, Bull. Seism. Soc. Am. 91, 739–752.