Seismic Hazard Analysis and Zonation for the northern Areas of Pakistan and Kashmir

by

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Preface

Population growth, modern economic developments, real time communication, and industrial interdependence among countries have sharpened the impact of natural disasters. Such calamities and miseries are now fortunately being given more global attention than before. The result is a realization that much can be done through rational studies and foresight to mitigate these risks to life and social well being. This is particularly true for the risk due to great earthquakes.

The 8th October, 2005, Muzafarrabad earthquake emphasized the importance of redefining the seismic zonation of Pakistan, as a basis for the revision of the building code of the country. The Pakistan Meteorological Department (PMD) took the responsibility to revise the seismic zonation of the country.

This study is particularly valuable in that it introduces new disciplinary approaches to both the mitigation of earthquake risk and post earthquake management of the disasters. The modeling of the ground motion, which is fundamental to earthquake hazard reduction, is done by using a probabilistic approach. This is accomplished by first creating a comprehensive catalogue of earthquakes based on different sources and reporting agencies within the region of interest [30-40^{o}N, 69-80^{o}E]. Since the quality of the catalogue is critical for the subsequent hazard and risk assessments special emphasis was given to that part of the work.

The present study is the first part of three-year cooperation between Pakistan Meteorological Department and NORSAR, Norway. This initial study, concerned with a seismic zonation of the northern areas of Pakistan, was conducted by Zahid Rafi and Ameer Hyder during an 8-week visit to NORSAR, as a first step in a longer effort within seismic hazard estimation for Pakistan. The funding of this study was provided by the Norwegian Ministry of Foreign Affaire through the Norwegian Embassy and by the Government of Pakistan under the project PAK-3004, Institutional Cooperation Program.

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Summary

In this study seismic hazard was computed for the northern Pakistan and Kashmir by using a probabilistic approach based on a regionalized earthquake source model established for this study. The source model was developed from carefully evaluated earthquake catalogues in combination with a seismotectonic evaluation of the region, and combined with a ground motion prediction model. The hazard has been evaluated in terms of spectral acceleration for a range of frequencies of engineering interest, using the computational program Crisis2003.

Fig.1 shows the peak ground acceleration (PGA) values for the entire study area, for return periods of 100, 500 and 1000 years. For 500 years the values range between 10 and 60 % of g (9.81 m/s^2), demonstrating a significant variation of seismic hazard within Pakistan. Equal-hazard response spectra have also been evaluated.

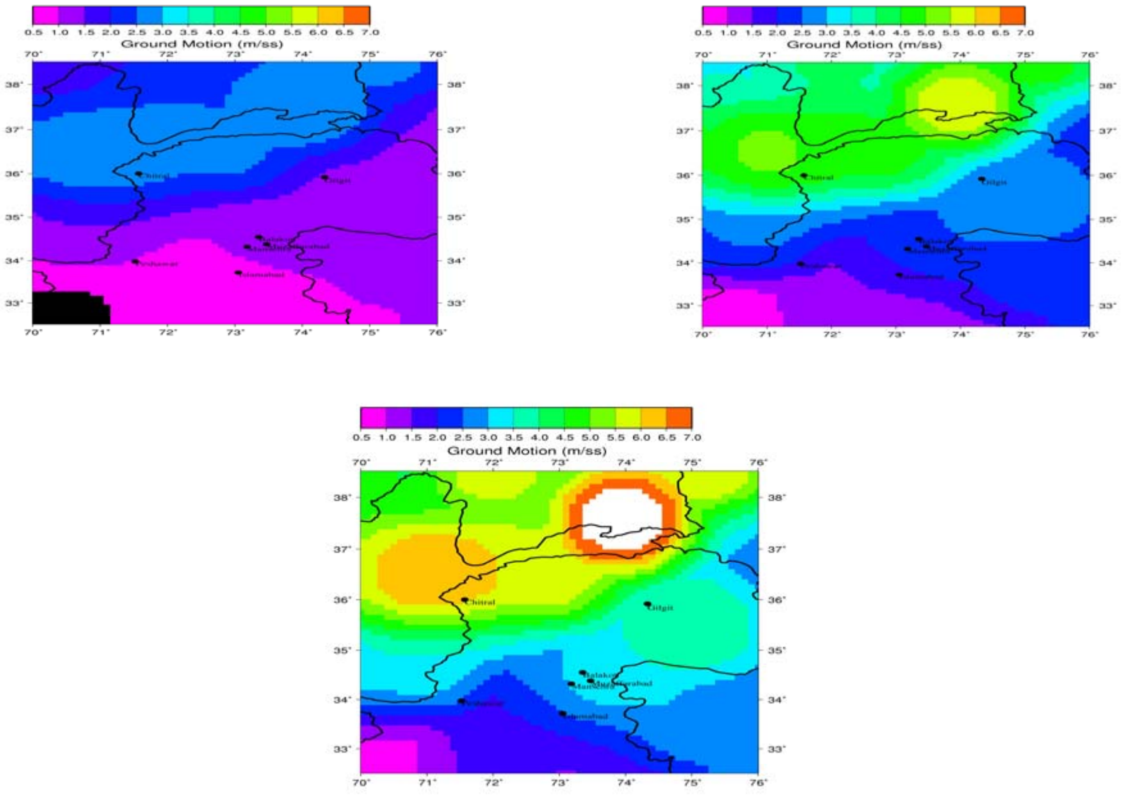


Fig. 1. Seismic hazard maps for northern Pakistan for return periods of 100 (upper left), 500 (upper right) and 1000 (lower) years.

1 Introduction

Pakistan has experienced many damaging earthquake over the last 100 years, including three disastrous earthquakes with magnitude above 8 and have struck this part of the Himalayan belt within the last 50 years. These are the Quetta Earthquake in 1935, the Makran Coast earthquake which generated a tsunami in 1945 and the recent Muzafarrabad Earthquake on 8th October, 2005. During the latter earthquake many concrete buildings in the northern parts of Muzafarrabad collapsed completely, killed their residents instantly. Massive landslides wiped out villages located on steep mountain slopes and rock avalanches severed the narrow highway that connects the mountainous region to the rest of the country. In the wake of this disaster, which killed at least 87,000 people and displaced many more, a strong consensus has emerged to prepare the nation in a better way for future earthquakes.

The 2005 earthquake occurred in the Indus Kohistan Seismic Zone (IKSZ) [Parson et al., 2006] with its epicentre in the Kishenganga (Neelum valley). The event was accompanied by rupture of the Balakot-Bagh fault along the Jhelum river near southeast of Muzafarrabad and further northeast near the town of Balakot in the north west frontier province of Pakistan.

This earthquake enhanced the consciousness about the increasing vulnerability that the growing population is confronted with, in particular since an increasing number of people are concentrated in cities, small and large, and frequently also in buildings with poor seismic resistance capacities. If this development towards an increasing vulnerability there will by certainty be more disastrous earthquake in this region.

This development is now being increasingly recognized by not only by Earth scientists and earthquake engineers, but also by the government, national, regional and local. It is now globally realized that poorly constructed buildings and houses are the main reason for the large number of victims in most earthquake disasters. The federal government of Pakistan soon realized this would call for a re-evaluation of the existing building code of Pakistan.

The Pakistan Meteorological Department (PMD), which is charged with the mandate of monitoring the earthquake activities in Pakistan, took the responsibility to revise the seismic zoning of Pakistan, in cooperation with NORSAR. As an initial effort a seismic zonation for the cities of Islamabad and Rawalpindi was completed in

February, 2006. The present report covers the seismic zonation of Kashmir and the northern areas of Pakistan.

2 Technical Approach

2.1 Design Codes and Construction Details

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 it contains key concepts that are applicable also to the present study. The seismic assessment has several key steps:

- Establishment of 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 the second bullet point 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.

The Peak Ground Acceleration (PGA) is the most commonly used measure of the ground motion used in seismic hazard analyses for many purposes, and it is the simplest way to characterize the damage potentials of an earthquake.

This study is entirely based on a probabilistic computation in which the expected ground motions are evaluated for various exceedance (or probability) levels. Naturally, the various seismic provisions and guidelines reflect first of all the seismicity level of the study area, where the expectance for the future is based on the past. The most detailed seismic code provisions come from region like Japan and USA where strong earthquake hit frequently in regions with complex infrastructure. In such countries the seismic awareness is very high due to a combination of past losses and an economic strength that facilitates effective counter measures.

The seismicity of Pakistan is, as already noted, characterized by important historical and recent major earthquakes, with a steadily increasing vulnerability of its northern and south-western regions. Unfortunately, the seismic awareness of these regions is still too low.

Seismic design codes have the purpose of providing guidelines for the reduction of both property and life losses due to the seismic events. These building design codes define standards for the seismic resistant design and construction of new building and for the retrofit of the existing ones. This set of guidelines is developed based on sound theoretical and physical modeling and on the observed damages caused by major earthquakes. The lessons given by past earthquakes help to promote advances in the development of design methods, the knowledge of materials performance and the enhancement of construction practices.

Basically, a seismic code contains specifications for the seismic hazard, including soil and possible near-fault effects that should be used in seismic design of buildings in the considered region, which in turn is based on a base shear load that a the building should resist. In Europe there has been a great effort in launching a set of Euro codes (EC), which contain complete guidelines for the building construction industries including the seismic provisions (EC-8, 2004). Euro code 8 defines two goals of the anti seismic design:

i- The structure shall be designed to withstand the design seismic action without local or general collapse.

ii- The structure shall be designed and constructed to withstand a seismic action (seismic load) having a higher probability of occurrence than the design seismic action.

Modern codes, notably the 1997 US Uniform Building Code (UBC-97, 1997) and the EC-8, 2004, are based on a specification of a base shear that depends on the seismic hazard level of the site, site effects from the site geology, near fault effects, weight, fundamental period, lateral forces, and the resisting system of the building. In areas of high seismicity, sufficient ductile detailing to accommodate the inelastic demand (Bachman and Bonneville, 2000) is needed.

The object of this study is to provide the seismic actions at various annual exceedance levels, or probabilities. The building constructors/designers must choose an appropriate risk level/exceedance probability level for the structure for 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 as 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 lifetime 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 in Fig. 2.1.

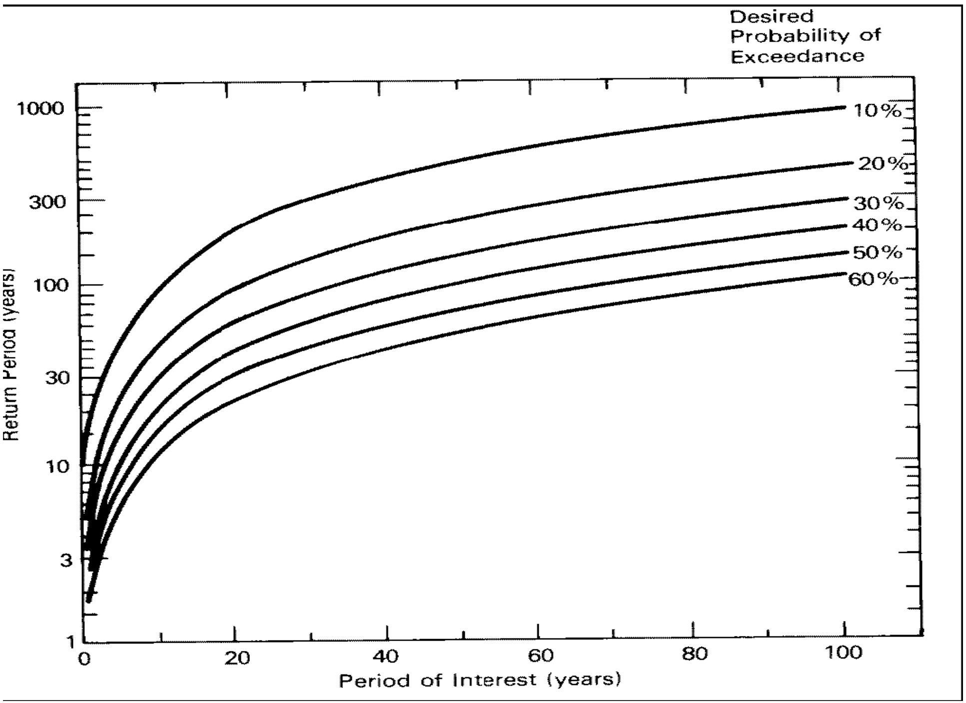


Fig. 2.1. Relationship between return periods (inverse of annual exceedance probability), period of interest and desired probability of exceedance during the period of interest. From Reiter (1990).

2.2 Methodology of Probabilistic Seismic Hazard Analysis

It is well known that uncertainties are essential in the definition of all elements that go into seismic hazard analysis. As might be anticipated this can sometimes lead to difficult choices for decision makers. Rational solutions to such dilemmas posed by uncertainty can be based on the utilization of some form of probabilistic seismic hazard analysis. In contrast to the typical deterministic analysis, which (in its simplest form) makes use of discrete single-valued events or models to arrive at the required description of earthquakes hazard whereas, the probabilistic analysis allows the use of multi-valued or continuous events and models. Of most importance, the probability of different magnitude or intensity earthquakes occurring is included in the analysis. Another advantage of probabilistic seismic hazard analysis is that it results in an estimate of the likelihood of earthquake ground motion or other damage measure occurring at the location of interest. This allows the incorporation of seismic hazard into seismic risk estimates. Probabilistic seismic hazard estimates can be expanded to define seismic risk.

The methodology used in most probabilistic seismic hazard analysis was first defined by Cornell (1968). There are four basic steps for assessment of PSHA.

Step 1 is the definition of earthquake sources. Sources may range from small faults to large seismotectonic provinces.

Step 2 is the definition of seismicity recurrence characteristic for the sources, where each source is characterized by an earthquake probability distribution or recurrence relationship. A recurrence relationship indicates the chance of an earthquake of a given size to occur anywhere inside the source during a specified period of time. A maximum or upper bound earthquake is chosen for each source, which represents the maximum event to be considered. Because these earthquakes are assumed to occur anywhere within the earthquake source, distances from all possible location within that source to the site must be considered.

Step 3 is the estimation of the earthquakes effect, which is similar to the deterministic procedure except that in the probabilistic analysis, the range of earthquake sizes considered requires a family of earthquakes attenuation or ground motion curves, each relating a ground motion parameter, such as peak acceleration, to distance for an earthquake of given size.

Step 4 is the determination of the hazard at the site, which is substantially dissimilar from the procedure used in arriving at the deterministic hazard. In this case the effects of all the earthquakes of different sizes occurring at different locations in different earthquake sources at different probabilities of occurrence are integrated into one curve that shows the probability of exceeding different levels of ground motion level (such as peak acceleration) at the site during a specified period of time. With some assumptions this can be written as:

$$E(Z) = \sum_{i=1}^{N} \alpha_i \int_{mo}^{ma} \int_{r=0}^{r=} f_i\,(m) f_r\,(r)\; P(Z>z|m,r) drdm$$

where E(Z) is the expected number of exceedances of ground motion level z during a specified time period t, α_i is the mean rate of occurrence of earthquakes between lower and upper bound magnitudes (m_o and m_u), f_i (m) is the probability density distribution of magnitude within the source I, $f_i(r)$ is the probability density distribution of epicentral distance between the various locations within source I and the site for which the hazard is being estimated, and P(Z>z | m,r) is the probability that a given earthquake of magnitude m and epicentral distance r will exceed ground motion level z.

It is usually assumed when carrying out the probabilistic seismic hazard analysis that earthquakes are Poisson distributed and therefore have no memory; implying that is each earthquake occurs independently of any other earthquake.

One of the most important of the recent developments within PSHA has been in seismic source modeling. Originally, seismic sources were crudely represented as line sources (Cornell, 1968) and later 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 Aug (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; Bommer et al., 2005), 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 at NORSAR into the 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 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.

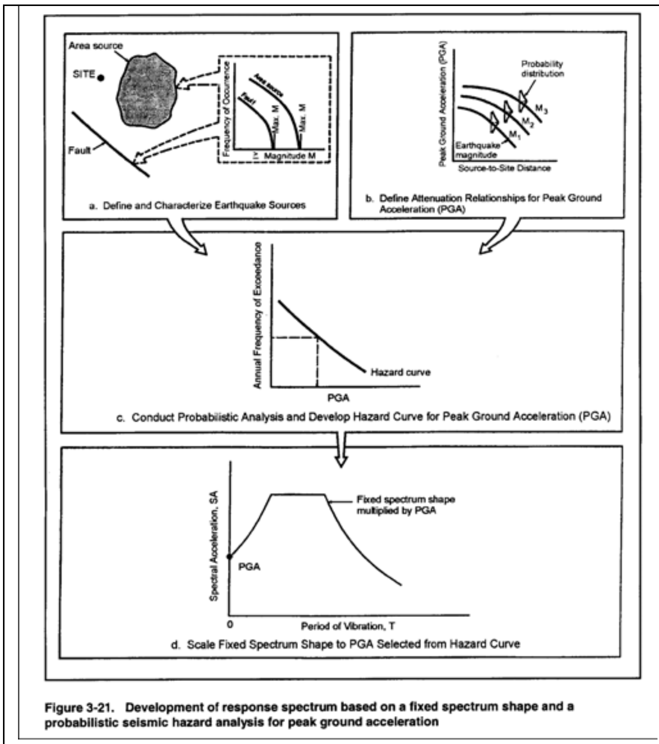


Fig. 2.2. Simple layout of probabilistic earthquake ground motion (GM) hazard computation, and the associated response spectrum with fixed shape.

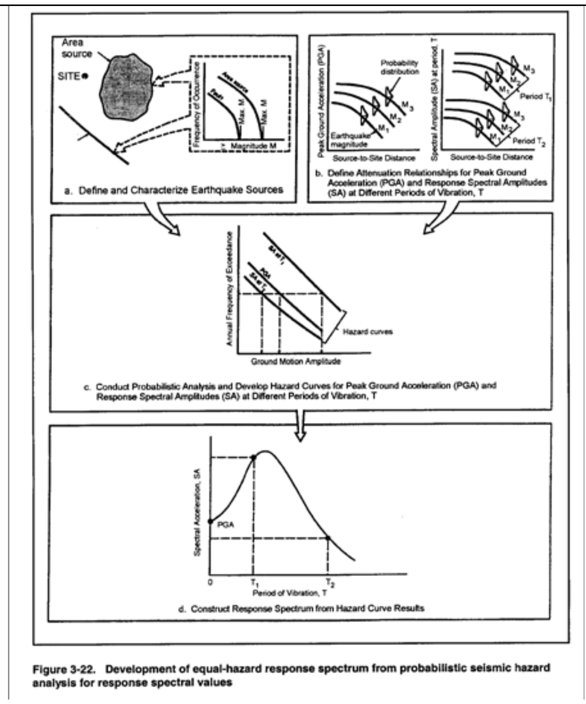


Fig. 2.3. Simple layout of probabilistic earthquake ground motion (GM) hazard computation, and the associated equal probability response spectrum.

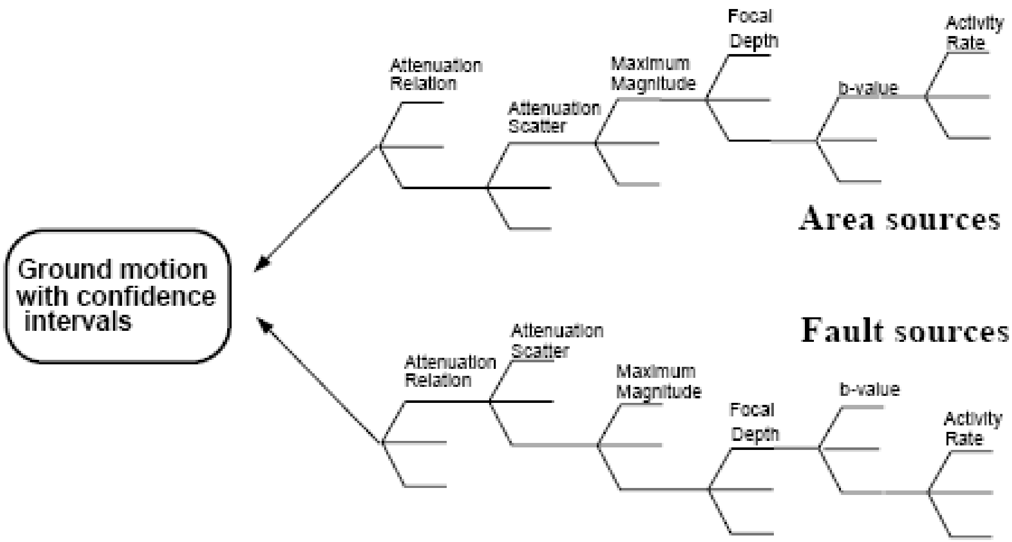


Fig. 2.4. Logic tree branches for seismic sources.

2.3 Probabilistic Seismic Hazard Analysis

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 the 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 uniformly 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 S_n 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

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

and where $\lambda_n(M_i \mid S_n)$ is the mean number of events per unit time of magnitude M_i ($M_i \in [M_{\min}, M_{\max}]$) in the source n with seismicity parameters S_n. Moreover, $P_n(z \mid M_i S_n)$ 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. The expression $G_n(z \mid r_j M_i S_n)$ is the probability that the ground motion level z will be exceeded, given an event of magnitude Mi 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/TR, where TR 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/TR 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 TR of 475 years (annual probability of exceedance 0.211 x 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.

2.3.2 The 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 $\beta = b*\ln(10)$ that describes the relation between the number of smaller 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 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 may be separately included as seismic sources in addition to area sources, are usually attributed their own b-values, which need to bear no immediate relation to the values obtained from the regional recurrence statistics.

2.3.3 Strong-motion (attenuation) models

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

$$\ln Z = c1 + c2\, M_i + c3 \ln R_j + c4\, R_j$$

where Z is the ground motion variable and c1 to c4 are empirically determined constants. Also found from the recorded data is an estimate of the distribution variance.

One of the most important sources of uncertainty in PSHA is the variability or scatter in the ground motion (attenuation) models, which is an aleatory uncertainty usually expressed through a sigma value which is often of the order of 0.3 in natural logarithms, corresponding to 0.69 in base 10 units. This uncertainty is expressing a basic randomness in nature and cannot be reduced with more data or knowledge. In PSHA we integrate over this uncertainty which thereby is directly influencing (driving) the seismic hazard results.

2.3.4 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, in this case area zones, parameter variability in maximum magnitude, focal depth, b-value and activity rate can be introduced as through 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 hazard 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

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 and to quantify the uncertainties in the final hazard characterizations (confidence limits).

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

- 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.

2.4.1 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 geological 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.

2.4.2 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 catalogue, also information which can improve the understanding of the geodynamics of the region, such as earthquake rupture processes, mode of faulting, stress field, etc.

2.4.3 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 catalogues) 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.

2.4.4 Ground motion (attenuation) 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 area, and in particular for the Himalaya region, where very few strong-motion observations exist in spite of a high seismicity level.

2.4.5 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.

2.4.6 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 may be 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 are specifically developed for bedrock outcrop (site with no soil). 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 Regional Geology

3.1 Tectonic Overview

It is well known that the collision of the Indian subcontinent with Eurasian continent forms the Himalayas. The Indian plate is bordered by spreading centres to the SW, by transform boundaries to the east and west and by a unique continental collision boundary to the north. An important feature of the northern collision is that volcanoes and deep seismicity are absent.

This indicates that Indian plate does not decent deep into the earth’s mantle immediately north of Himalaya; Moreover, the absence of heavy down going slab means that the forces driving the collision process must largely originate either beneath the Indian plate or at the Indian Ocean spreading centres to the south. These forces subject the Indian plate to NE directed compressional stress.

3.2 Himalayan Geology

Great earthquakes are poorly known in this region prior to 19th century and even 20th century moderate and major events are not well studied seismically (Molnar. et al 1975).

The Pamir-Himalaya Arc is outlined by the convex-northward curvature of the Pamir, Hindokush, Karakorum, and the Pakistan Himalaya. Within the concave side of the arc lies the Hazara-Kashmir syntaxis. (Wadia, 1931) adapted this terminology and named correspondingly the Pamir-Himalaya Arc and Hazara-Kashmir syntaxis. Northeast of the Hazara-Kashmir syntaxis the geological structures are bent around the Nanga Parbat-Haramosh massif. The Himalayas represent one of the primary compressional features resulting from the collision between the Asian mainland and the Indian peninsula, Gondwanaland.

Unlike the setting of continent-ocean collisions the descending footwall is not covered by an ocean and can be instrumented in great detail. A belt of strong earthquakes is located south of the edge of the Tibetan plateau along a small circle with a radius of 1700 km . The 1885 Kashmir, 1905 Kangra, 1991 Utterkashi and 1994 Chamoli and 2005 Kashmir earthquakes appear to sequence along this small circle. The great shallow thrust earthquakes that are responsible for transferring the Himalaya southward over northern India occur south of this strong earthquake.

3.3 Geology of Northern Pakistan

Structural features in northern Pakistan are dominated by syntaxial bend of the Himalayas and associated with convergence of the Hidukush and Karakorum mountains. In the Kashmir Himalayas, cast of NW-SE, probably located expressions of the main boundary thrust (MBT) which is generally recognized farther east along most of the Himalayan front (Armbruster et al, 1978). These two faults, Murree thrust, which separates the tertiary Murree formation from overriding carboniferous Panjal formation, and the Panjal thrust, which separates the carboniferous rocks from the overriding Precambrian Salkhalla formation bend sharply around the syntaxis at about 73.5E^{o}. Generally, the trends of most features in northern Pakistan reflect the existence of the western Himalayan syntaxis. However, this trend is not evident in lower crustal seismicity. For example, the Pattan earthquake occurred within what has been termed the Indus Kohistan Seismic Zone (IKSZ) (Armbruster et al., 1978;

Seeber and Jacob, 1977), a straight NW-SE extension of the Murree and Panjal Thrust and MBT. The IKSZ was recognized on the basis of microseismicity at depth greater than 12km that was observed since the installation of Tarbela seismicity network.

3.4 Himalayan Seismicity

Fig. 3.1 shows the tectonic setting of the northern areas of Pakistan.

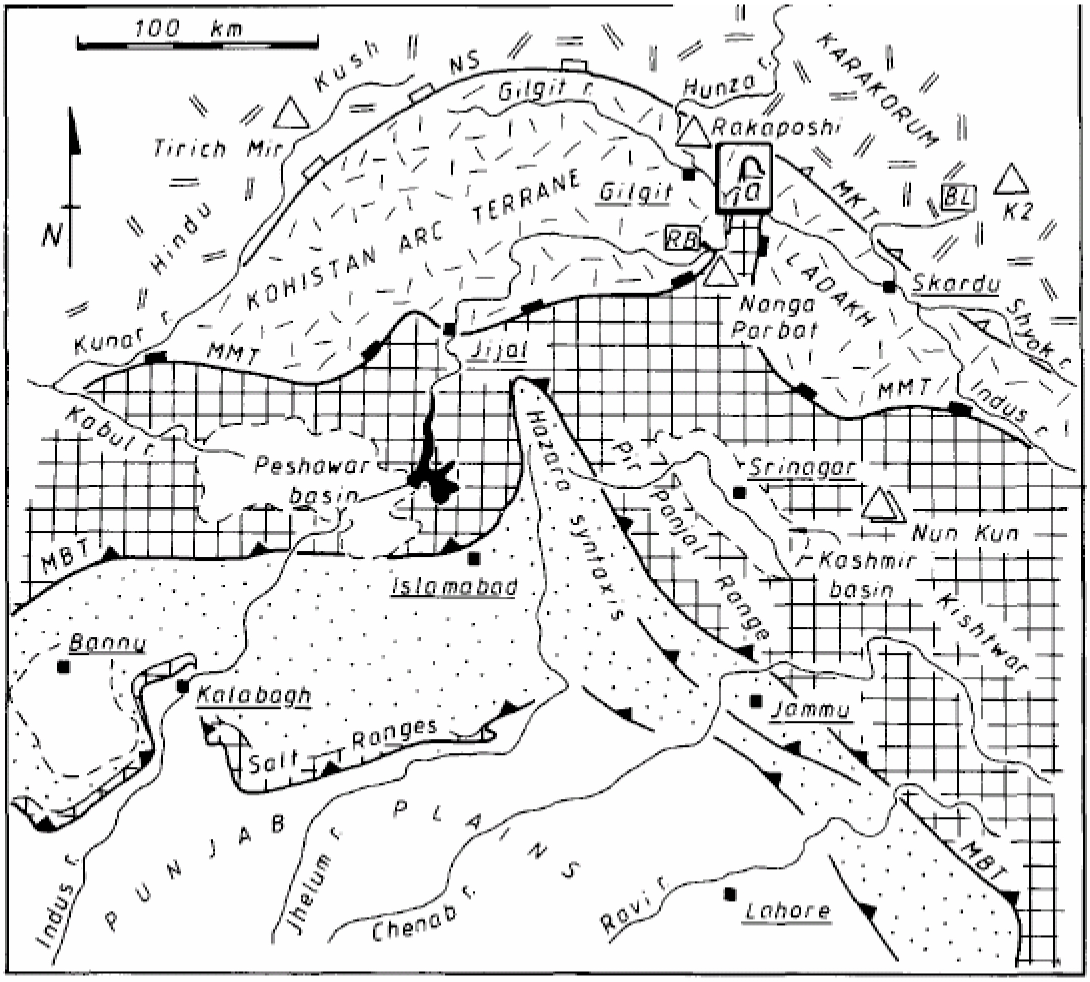


Fig 3.1. Sketch map of the NW Himalayas showing the positions of major thrust and sutures, Main Mantle Thrust, MMT, NS, northern Suture of Kohistan, Main Boundary Thrust, MBT, RB, Raikot Bridge, BL, Baltoro Leucogrenities , by G.Gangotri, M.Manaslu, L.Langtang.

The severe human and economic effects of the earthquake have uniquely influenced our understanding of seismic hazard in the western Himalaya. The rocks exposed in the Himalaya consist of material that was part of the Indian subcontinent since being deposited or consolidated and rejuvenated. The geological structure appears to be created by E-W compression, tear faulting, strike-slip and reverse block movement. For example, Seeber and Armbruster (1981) interpret the Kangra (1905) earthquake to have ruptured an area of size 280 x 100 km2, which when combined with the inferred rupture areas of the 1897,1934, 1950 and 2005 earthquakes implies that more than half of 2000-km long Himalayan arc has been ruptured by these great earthquakes. The rupture of the remaining area of the Himalaya arc in future, fro example in terms of major earthquakes to the west and east of the Kangra rupture zone poses a significant hazard to the greatly increased population that now inhabit the plains fronting the Himalaya.

3.4.1 The M 8.0 Kangra earthquake, 1905

The Kangra earthquake with magnitude, Ms= 8.0 (Gutenberg and Richter) of 4 April 1905 in the north-west Himalaya was the first of several devastating 20^{th} century earthquakes to occur in northern India. More than 20,000 people were killed near the epicentre area and about 100,000 buildings were destroyed by this earthquake. Although this earthquake is not the only severe event known in the western Himalaya, it has the largest death toll and is one of the first to have occurred since the development of the instrumental seismology. It is also one of the four great Himalayan earthquakes to have occurred in the past 200 years.

The estimated magnitude of the Kangra earthquake has also influenced seismological thinking on the largest credible earthquake that might occur in the western Himalaya. Moderate earthquakes occur every few decades along the small circle that defines the southern edge of the Tibetan Plateau, but no historical earthquakes have ruptured the surface along the Main Frontal Thrusts bordering the Himalayan foothills. The 1905 event produced no frontal rupture.

Though historical records are poor, it appears that the last great earthquake in this region occurred in September 1555. Yet another major earthquake occurred in 1885 near Srinagar. Seeber and Armbruster (1981) found evidence of strain accumulation in the region.

Figure 3.2 shows the distribution of intensities from the Kangra earthquake (Chander, 1988; see also Ambraseys and Bilham, 2000)..

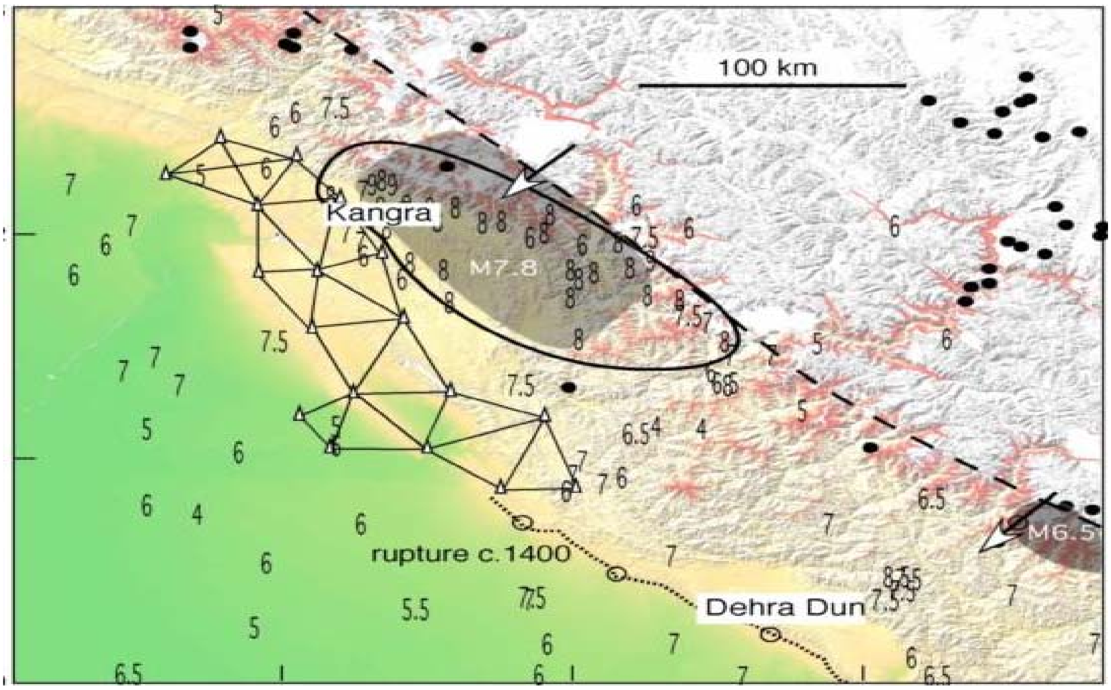


Fig. 3.2. Geodetic control points and newly evaluated felt intensities (Ambraseys and Douglas, 2004) from the Kangra 1905 earthquake. Previous investigations had speculated that the Dehra Dun 1905 intensity anomaly was caused by a triggered earthquake (Chander, 1988), but independent support appeared unlikely to be forthcoming. A careful search through surviving European seismograms of Kangra earthquake, however, confirmed seismic phases in the coda of the primary shock that are likely to have originated from this triggered earthquake.

3.4.2 The M= 6.0 Pattan earthquake, 1974

A few moderate magnitude earthquakes have occurred in the IKSZ, but the most destructive earthquake occurred on 28th December 1974 earthquake, magnitude 6.0 Richter scale, near Pattan. This earthquake occurred in the remote and mountainous region of northern Pakistan, resulting in the loss of life and damage to property. The focal mechanisms of this and six other moderate magnitude earthquakes since 1976 show consistent reverse motion on a plane dipping towards northeast.

Three great earthquakes with magnitude greater than 8 have been struck the Himalayan belt within a span of 50 years and the 1905 Kangra earthquake is one of them, which occurred in Himachal Pradesh, killed 18,815 people. The epicentre was located at 32.5^{o}N and 76.6^{o}E and had a shallow focus. The magnitude was estimated at 8.6 Richter scale and intensity reached to X (Rossi-Forel) in the epicentral region. The epicentre was located north of the active faults, MBT, Main Boundary Thrust, PT, Panjal thrust in the Chamba region (Thakur et al., 2000).

3.4.3 The M 7.6 Muzafarrabad earthquake, 2005

Geographically, the recent earthquake of 8th October 2005 (Mw 7,6) occurred in the Kashmir region, but whether its location is in the said Kashmir seismic gap region is still under discussion. The United States Geological Survey (USGS) and European-Mediterranean Seismological Centre (EMSC) have reported the epicentre of this earthquake in the syntaxis, while the Indian Meteorological Department (IMD) has reported it further west. Aftershocks of the earthquake as reported by Pakistan Meteorological Department (PMD) and USGS lie further NW of the main shock epicentre and beyond the syntaxial bends in the Indus Kohistan Seismic Zone.

This earthquake occurred on pre-existing active faults. Aftershocks and fault lines are shown in Fig. 3.3. The newly deformed area occupies a 90-100 km long northeast trending strip extending from Balakot, Pakistan, southeast through Azad Kashmir. The heavily damaged area north of Muzaffarabad, Kashmir shows the maximum deformation. There are known active faults stretching to the northwest and southeast near the epicentre, which reveal some uplift on the northern side and dextral, right-lateral strike-slip activities (Fujiwara et al., 2006). The known active faults are divided in two fault groups, the Muzaffarabad fault, northwest of Muzaffarabad and the Tanda fault, southeast of Muzaffarabad (Nakata et al., 1991).

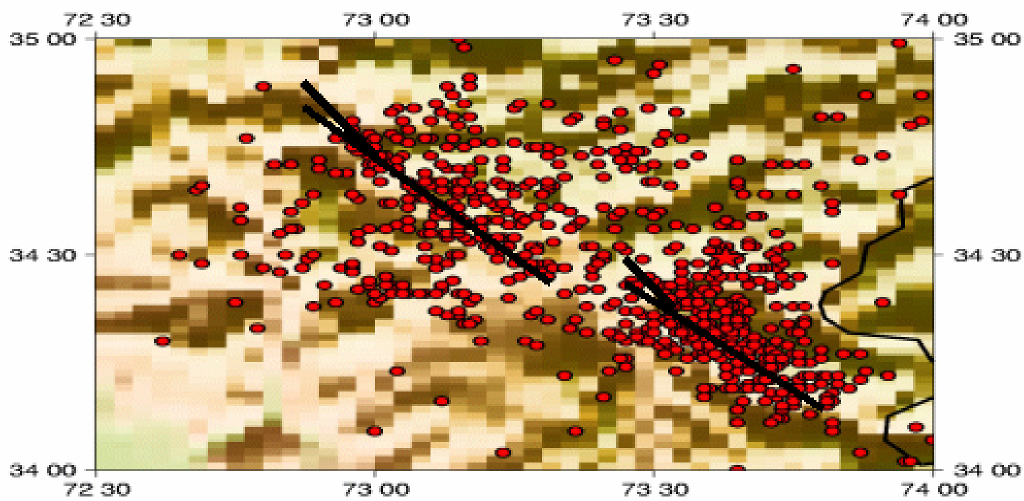


Fig. 3.3 Aftershocks data of 8th October, 2005, Kashmir earthquake, recorded by a mobile seismic network by PMD and a Chinese team.

Seismically, the most active geological structure of this region is considered to be capable of generating large events. However, it not appropriate to equate the IKSZ with MBT, because the tectonic history of these two are quite different. The activity along the IKSZ is much more intense than the MBT. Fig. 3.4 shows the distribution of crustal deformation in the larger epicentral region, as inferred from satellite observations.

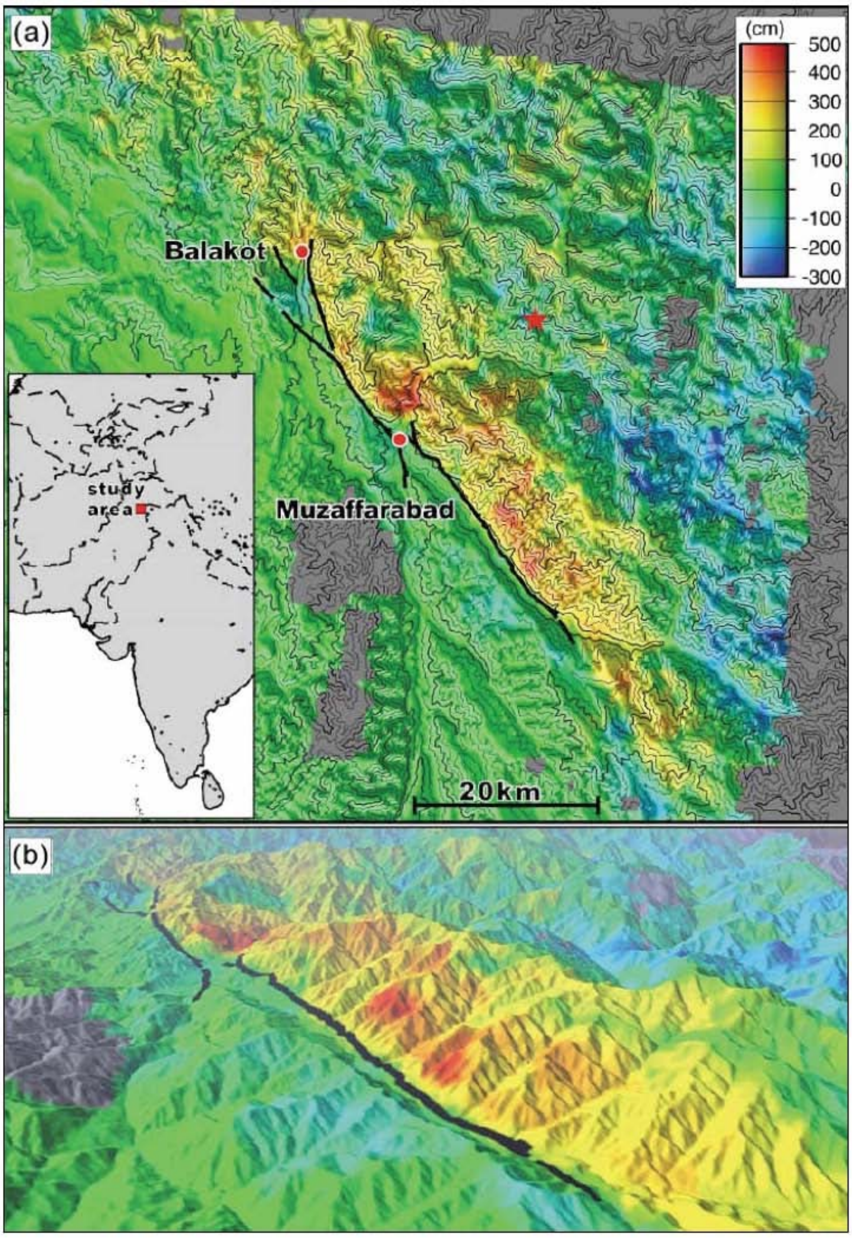


Figure.3.4. (a) Crustal deformation map for the 2005 earthquake, superimposed on topography and the location of known active faults. The red star shows the epicentre and black curve show the locations of active faults. Source generated by NASA Shuttle Radar Topography Mission. (b) A bird eye view of crustal deformation and active faults from the south.

3.5 Seismology of the Study Region

3.5.1 Earthquake databases

The catalogue established for this study was prepared as the first step in a longer process. This catalogue is primarily concerned with the analysis of the seismic hazard estimation. For this purpose a number of earthquake catalogues were evaluated. The NORSAR data base was used as one of the basic sources of information in this respect since it is based on reports from a large number of international seismological networks and reporting agencies. For the present study these include:

- i- The GAN database
- ii- The GUT database
- iii- The ABE database
- iv- The IRK database
- v- The ISC database
- vi- The BJI database
- vii- The Lee database
- viii- The EHB database
- ix- The PMD database
- x- The NORSAR database (a merged database established by collecting data from agencies worldwide)

The PMD database, which is the other main source of information in the present study, covers historical earthquakes and the most recent instrumental earthquakes. Pakistan Meteorological Department established its own seismological network in 1954. The PMD catalogue contains data since from 1905, but those data were included from the ISC data base, for locations in and around the Pakistan. These data were not sufficient for the zonation, however, so it was necessary to supplement with another data base with a wider spatio-temporal coverage. To this end the NORSAR data base fulfils this requirement.

Among the many reporting agencies contained in the NORSAR catalogue it soon became clear that it was the data from the International Seismological Centre (ISC) data base that would have to constitute the backbone of the catalogue, supplemented with data from PMD and some other sources. These are the seismicity data which have served as a basis for the quantification in each of the source zones defined and analyzed in the present study.

3.5.2 The largest earthquakes

As an example of what the earthquake catalogue contains we have in Fig. 3.5 plotted the principal events with magnitude 7.0 and above in the study region, as also listed in Table 1, since year 1900.

Figure 3.5 Earthquakes with magnitude (Ms) greater than, equal to 7.0 in the study region, showing that most of the major earthquake occurred in the northern and north-western Pakistan.

Table 1: Principal events, Magnitude Ms≥ 7.0 in the study region since year 1900, with origin time (year, month, day), latitude and longitude (degrees), focal depth (km) and magnitude.

Year	Month	Day	Lat	Long	Depth	M_S
1902	8	22	40.000	77.000	-----	7.7
1902	10	6	36.500	70.500	200	7.2
1905	4	4	33.000	76.000	-----	7.8
1907	10	21	38.000	69.000	-----	8.0
1907	4	13	36.500	70.500	260	7.0
1908	10	23	36.500	70.500	220	7.0
1908	10	24	36.500	70.500	220	7.0
1909	7	7	36.500	70.500	220	7.8
1909	10	20	30.000	68.000	0	7.2
1911	7	4	36.000	70.500	190	7.6

1911	2	18	38.200	72.800	26	7.4
1917	4	21	37.500	70.500	-----	7.0
1921	11	15	36.335	70.763	215	7.8
1922	12	6	36.931	70.838	230	7.5
1924	10	13	36.576	70.607	220	7.3
1929	2	1	36.054	70.679	35	7.1
1931	8	24	30.300	67.800	-----	7.0
1935	5	30	29.500	66.800	-----	0.0
1937	11	14	36.804	70.719	240	7.2
1943	2	28	36.300	71.000	223	7.0
1944	9	27	38.500	74.800	-----	7.0
1949	3	4	36.700	70.500	223	7.5
1949	7	10	39.200	70.700	-----	7.5
1950	7	9	36.700	70.500	223	7.5
1951	1	6	36.500	71.000	223	7.5
1951	6	12	36.300	71.000	223	7.5
1955	4	15	39.900	74.700	-----	7.0
1956	6	9	35.031	67.476	35	7.5
1965	3	14	36.400	70.700	200	7.6
1965	3	14	36.401	70.713	210	7.6
1974	8	11	39.377	73.800	3	7.2
1983	12	30	36.386	70.712	215	7.4
1985	8	23	39.440	75.240	20	7.3
1985	8	23	39.445	75.241	20	7.3
1985	7	29	36.164	70.863	100	7.0
1985	7	29	36.160	70.890	100	7.0
1993	4	19	36.460	71.820	211	7.0
1993	8	9	36.327	70.874	211	7.0
1996	11	19	35.368	78.167	7	7.1
1996	11	19	35.360	78.160	33	7.0
2002	3	3	36.465	70.458	230	7.4
2005	10	8	34.539	73.588	26	7.7

3.5.3 Catalogue completeness

The time-magnitude plots were made for the catalogues from PMD and NORSAR (see Section 3.5.1) as shown in Fig. 4.4. The figure demonstrates that the PMD catalogue can be regarded as being reasonably complete for M> 4.5 only from the late 1980's, whereas the NORSAR catalogue has data since 1900 only for magnitude above 6.6 but after 1950 much data are available even for magnitudes below 4.0. It is worthy to note that the two major improvements in seismicity coverage occurred in the early 1960's (the WWSSN network) and around 2000.

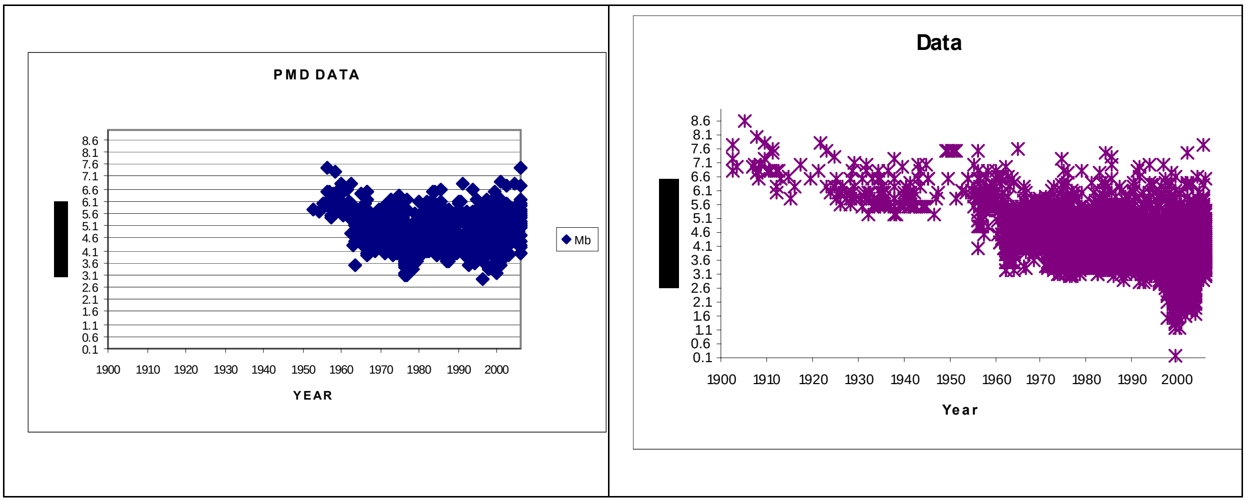


Fig. 4.1. Time-magnitude plots for two catalogues for the identification of magnitude completeness thresholds. Left: PMD data which started from 1954 and before that data was taken from other international catalogues. Right: PMD and International data collected for the region 30-40^{o}N and 65-80^{o}E.

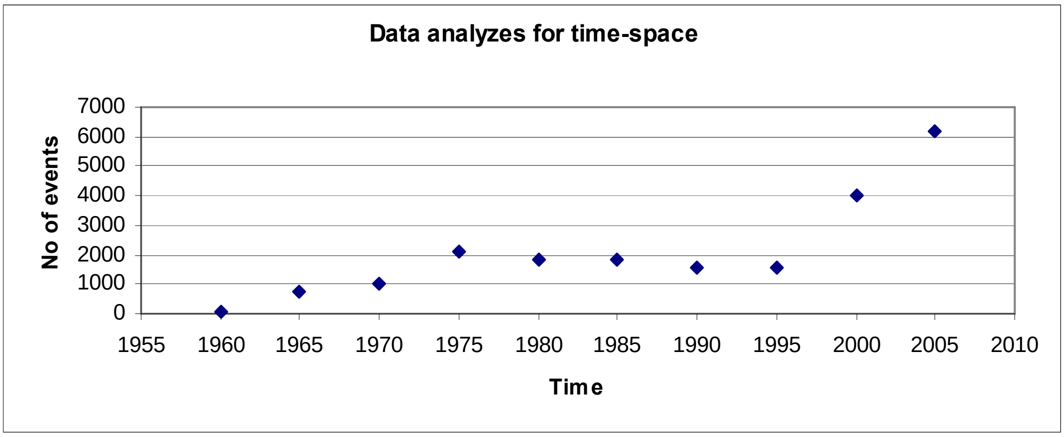


Fig. 4.2 Data analyzed for time-space (1960-2005) number of events recorded per five years that indicates the capability of recording the earthquakes by world seismological networks is increased.

4 Seismotectonic Interpretation

Based on the above geotectonic, structural geological and earthquake information the division into eleven distinct source zones was 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 km 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.

4.1 Seismic Provinces and Area Sources

The whole study area was divided into 16 seismic zones. The division was based on the data processing of the whole catalogue regarding the seismicity, depth and the study of research papers. The zones are defined in the figure below. The Hindu- Kush, northern areas and Kashmir are the most active zones. In our computational model

these zones are very critical and have much influence on the seismic hazard of the study areas. The sixteen seismic zones are described in Table 4.1.

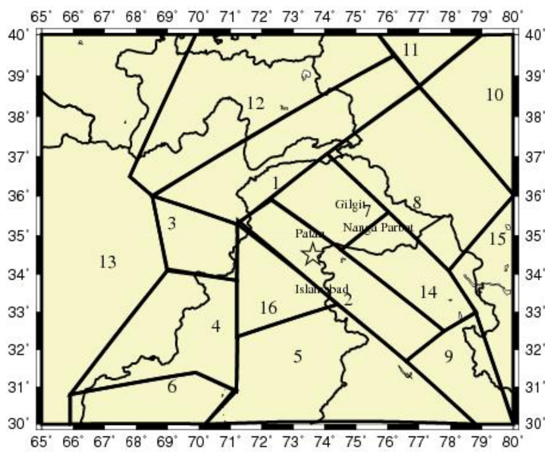
Table 4.1: Area zones used in the seismic hazard analysis.

Zone Number	Region (30-40^{o} N to 65-80^{o}E)
0	Whole study area
1	Hindukush and Pamir belt, seismically active region
2	Kashmir region, active seismic zone
3	North-eastern Afghanistan, low seismicity
4	Western Baluchistan and southeast Afghanistan, low seismicity
5	Central Pakistan, low seismicity
6	Northern Baluchistan, seismically active region
7	Northern Pakistan, seismically active region
8	China-Pakistan border, active seismic region
9	Himalaya-Indian portion, active seismic zone
10	China, low seismicity
11	Extreme southwest China, high seismicity
12	Afghanistan-Tajikistan, active region
13	Central & Southern Afghanistan, low seismicity
14	Indian Kashmir, low seismicity
15	Jammu & Kashmir, low seismicity
16	Northern Punjab, low seismicity

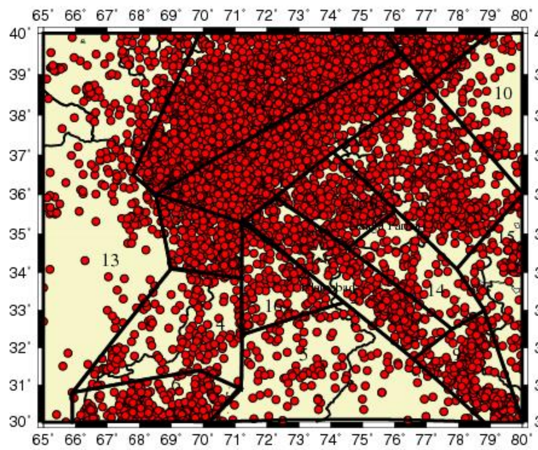
4.2 Regional Seismicity and Magnitudes

The combination of PMD and international data bases results in a catalogue with different kinds of magnitudes, essentially body wave magnitude (m_b) for the smaller events and surface wave (M_S) and moment (M_W) magnitudes for the larger events. Since we need to base the hazard estimation on M_S, partly because that is what the ground-notion relations require, this should ideally call for a conversion between the different magnitudes. In the lack of such conversion relations, however, we have in the present study simply used nominal m_b values and treated them as Ms in the cases when an original M_W or M_S value was not available. The fact that we still get a b-value of very close to 1.0 for the larger region under study shows that this works reasonably well.

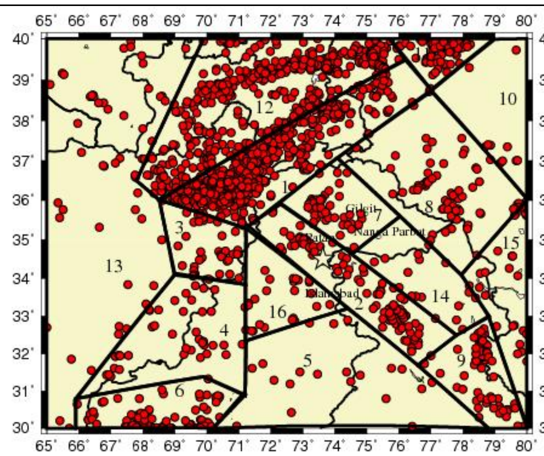
Fig. 4.3 illustrates the seismicity at different magnitudes and depths of the sixteen sub seismic zones of our study area.



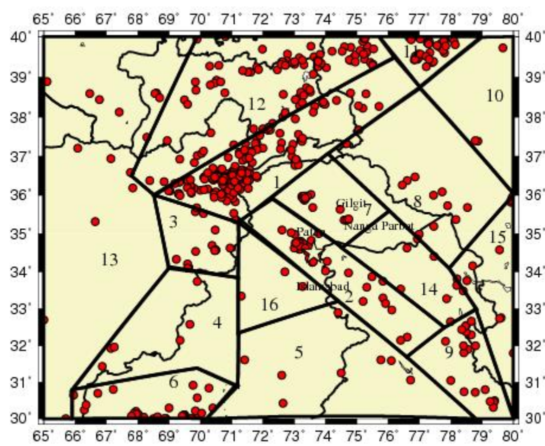
Zone distribution with numbers



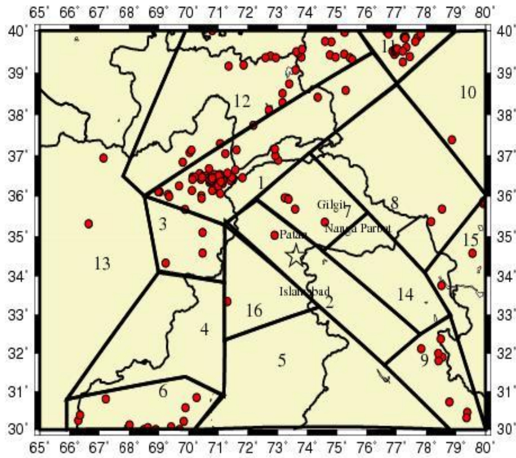
Magnitude >3 for all depths



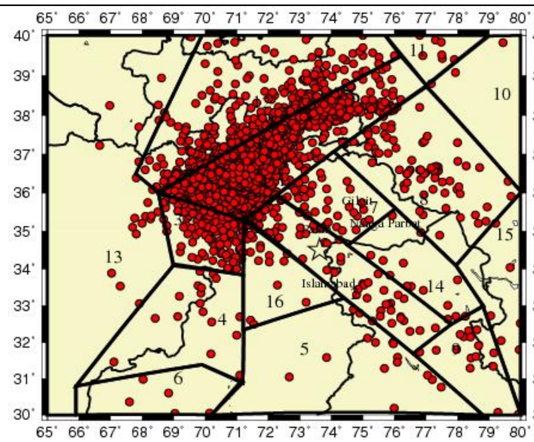
Magnitude >4.5 for all depths



Magnitude >5.5 for all depths



Magnitude >6.5 for all depths



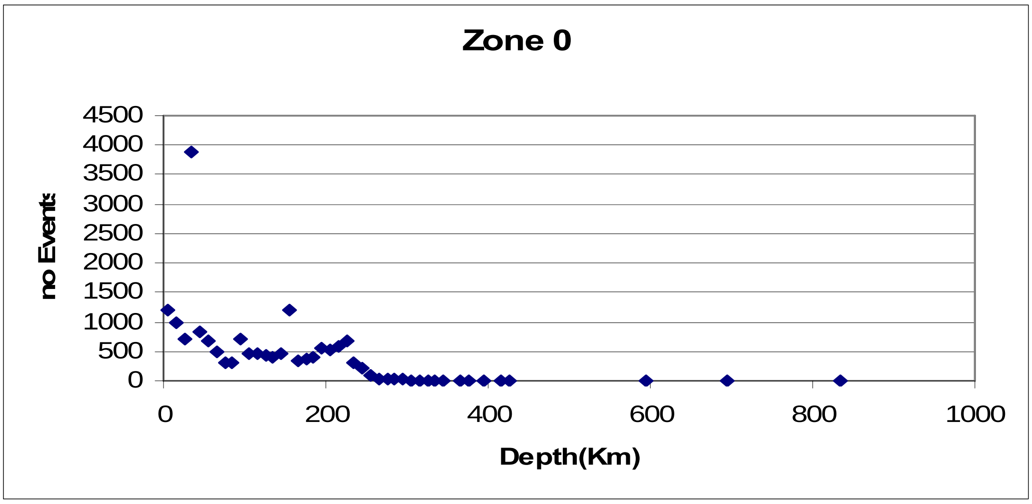
Depth > 100 km for magnitudes > 3.5

Fig. 4.3. Plotting of events at different magnitudes (Ms) and depths for the sixteen seismic zones in the study area.

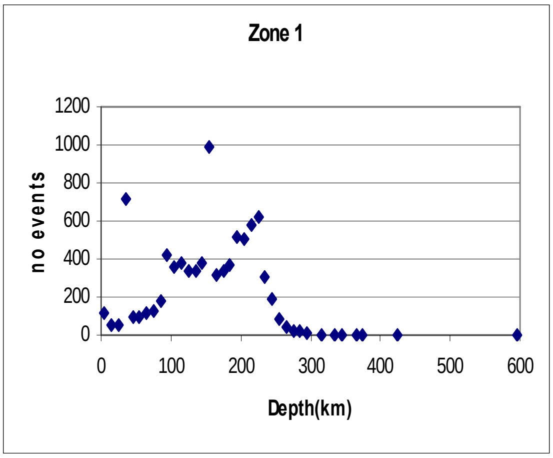
4.3 Focal Depths

The sequence of plots in Fig. 4.4 shows the seismicity pattern with respect to depths for each of the zones. What is seen there is that most of our study region reveals intermediate to deep seismicity with only few earthquakes at shallow depth. This is of course important with respect to the seismic hazard of this area, since increasing focal depths decreases the hazard. It is clear, however, that zones 1, 2, 3 and 7 (see Table 4.1) have particularly deep seismicity, dominated by Hindukush.

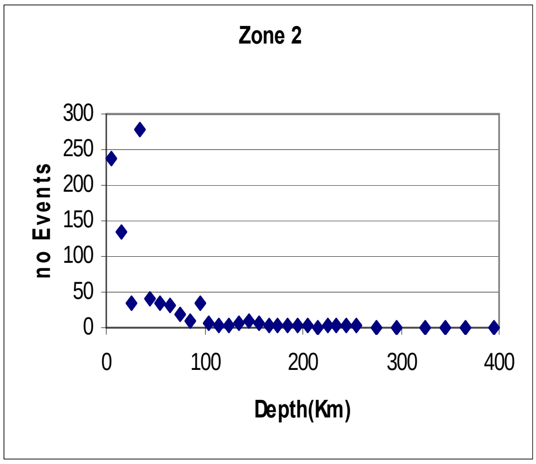
For the plots in Fig. 4.4 it should be noted in particular that the large number of events with a nominal depth of 33 km refer to the USGS (PDE) assessment of 33 km in cases when this only means that they are crustal events.



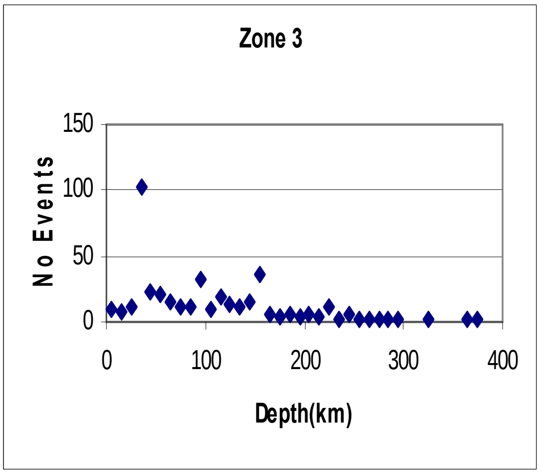
whole area zone 0

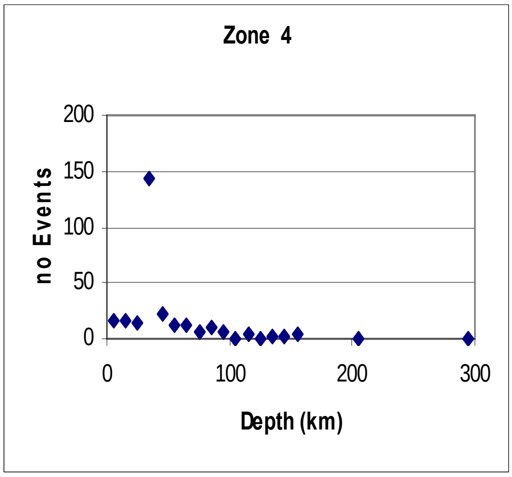

Zone 1
1200
1000
800
600
400
200
0
no events
0
100
200
300
400
500
600
Depth(km)

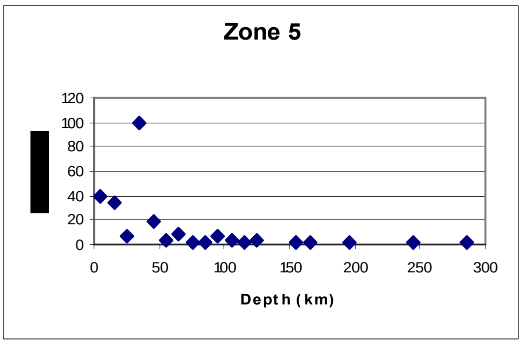
Zone 1

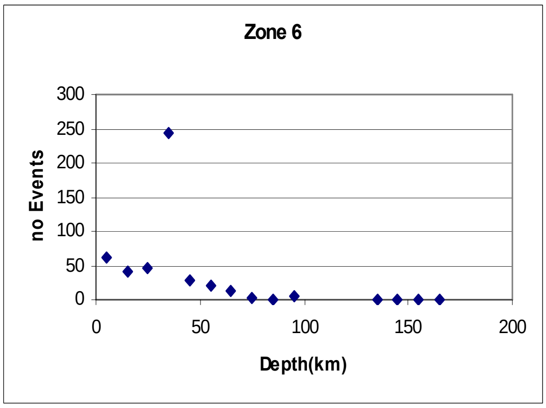

Zone 2
300
250
200
150
100
50
0
no Events
0
100
200
300
400
Depth(Km)

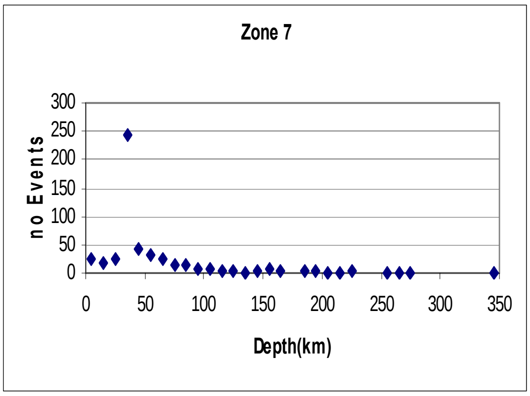
Zone 2

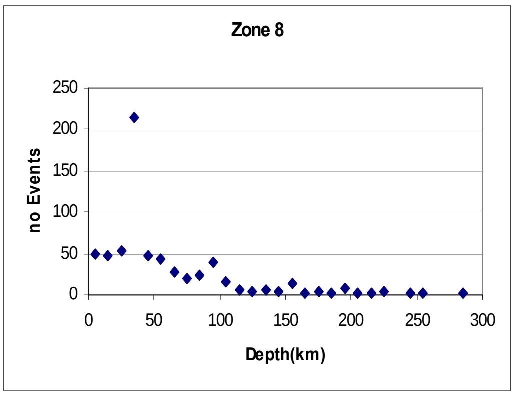

Zone 3
150
100
50
0
No Events
0
100
200
300
400
Depth(km)

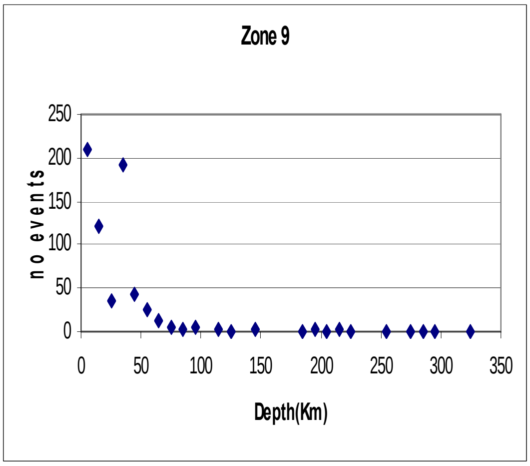

Zone 4
200
150
100
50
0
no Events
0
100
200
300
Depth (km)

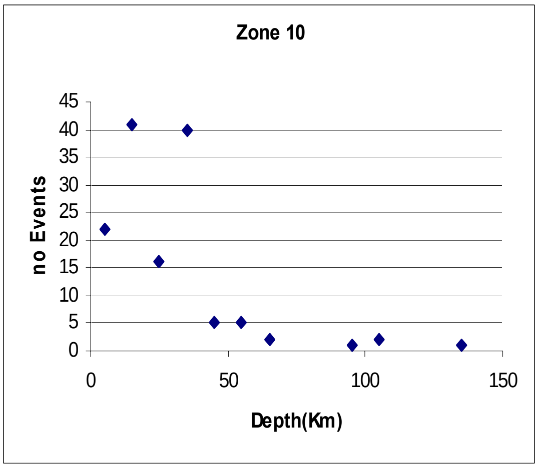

Zone 5
[redacted]
120
100
80
60
40
20
0
0
50
100
150
200
250
300
Depth (km)

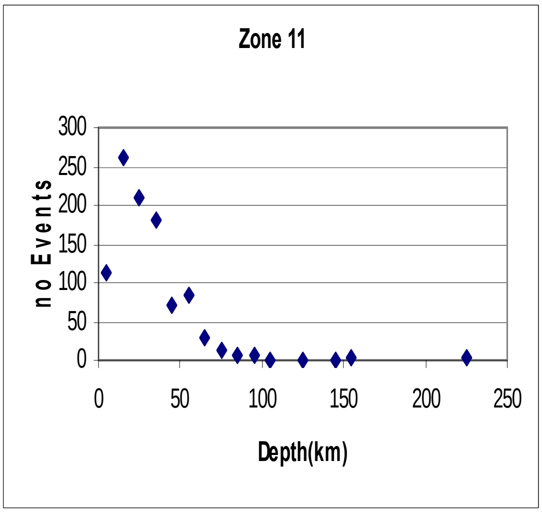

Zone 6
300
250
200
150
100
50
0
no Events
0
50
100
150
200
Depth(km)

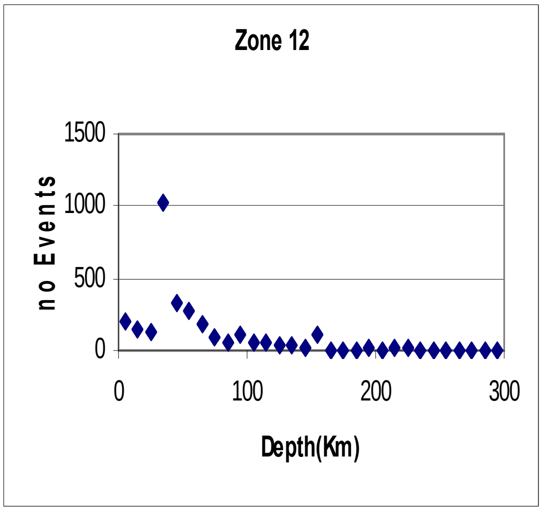

Zone 7
no Events
0 50 100 150 200 250 300
0 50 100 150 200 250 300 350
Depth(km)


Zone 8
no Events
0 50 100 150 200 250
0 50 100 150 200 250 300
Depth(km)


Zone 9
no events
0 50 100 150 200 250
0 50 100 150 200 250 300 350
Depth(Km)


Zone 10
no Events
0 5 10 15 20 25 30 35 40 45
0 50 100 150
Depth(Km)


Zone 11
no Events
0 50 100 150 200 250 300
0 50 100 150 200 250
Depth(km)


Zone 12
no Events
0 500 1000 1500
0 100 200 300
Depth(Km)

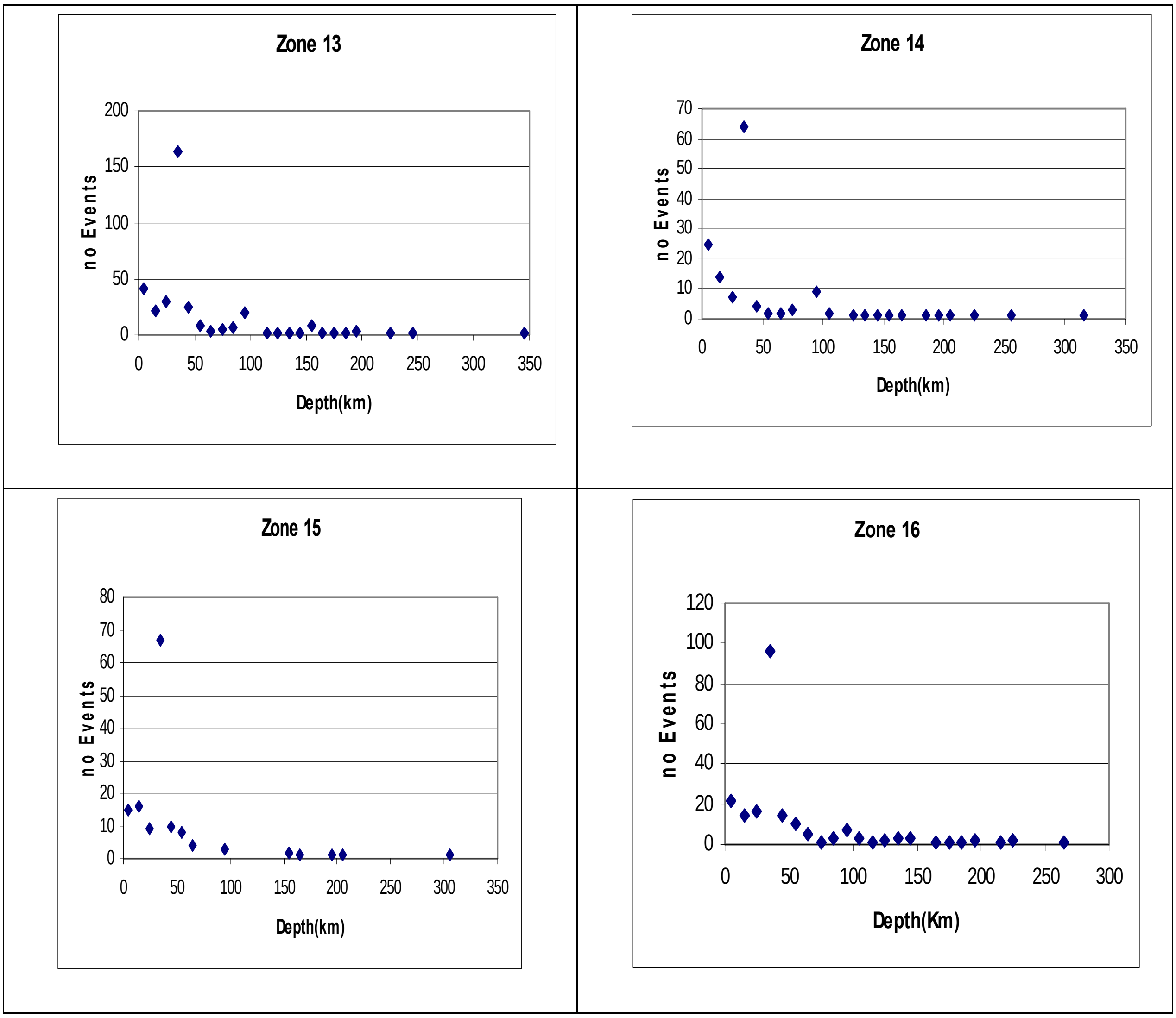


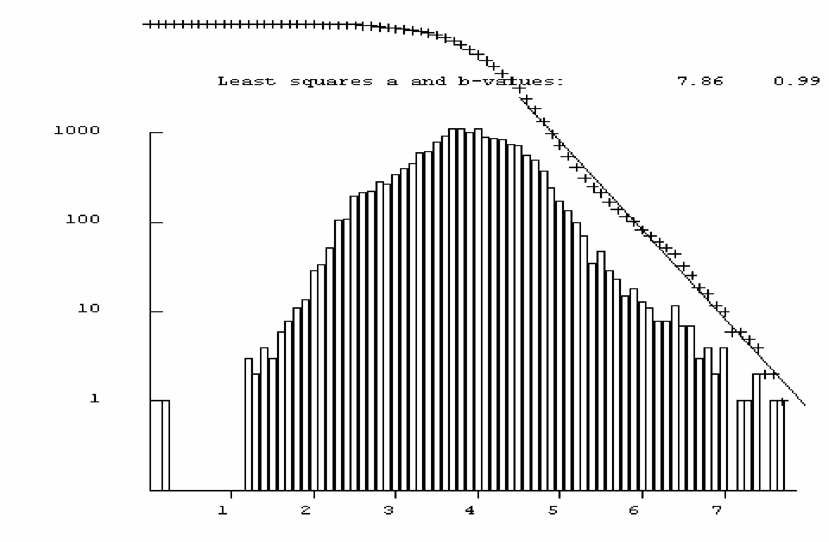
Fig. 4.4. Focal depth distribution for each of the each of the zones 0 (the entire region) to 16. See Table 4.1 and the first frame in Fig. 4.3 for zone definitions.

5 Quantification of Earthquake Recurrence

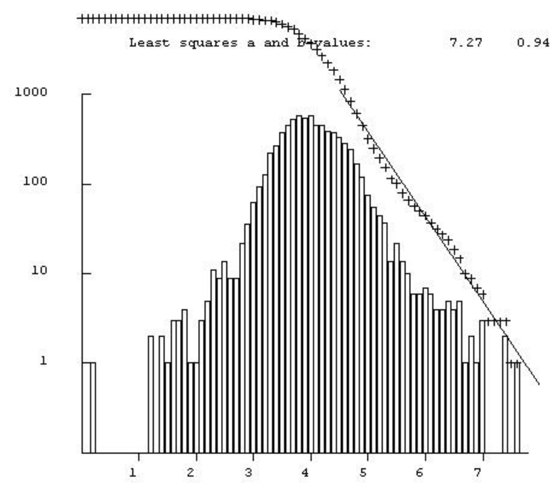
The basic input for the seismic hazard analysis is the source model, expressed through the activity rates 'a' and the b-values for each seismic zones. Using the established catalogue these have been carefully established through regression analyses, also for a zone 0 that comprises all of the other zones, as shown in Table 5.1. We used the 15 seismic zones as defined above, a division that was based on the complete seismicity analysis of the whole area. The zone 1, 2 and 7 were the most critical and has much influence on the hazard assessment.

The maximum magnitudes (M_{max}), also essential for the hazard level, were for each of the zones defined through a combination of the observed maximum magnitude for each zone and the evaluated tectonic potential, where a basic and commonly applied rule is that M_{max} should be set to 0.5 magnitude units above the largest historical value, unless this is very high. Table 5.1 shows the M_{max} values used in the computational model.

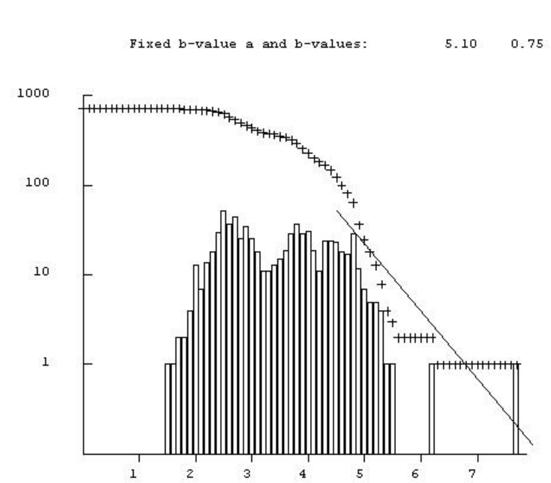
The plots in Figure 5.1 summarize the regression values for each zone, specified in terms of ‘a’ (level of seismicity) and ‘b’ (the slope) values. These are computed very carefully because these values largely drive the hazard. Zones 1 and zone 2 (see Table 4.1) are particularly important for the hazard assessment as these have the strongest influence on the ground motions in the study area.



whole area zone 0



Zone 1



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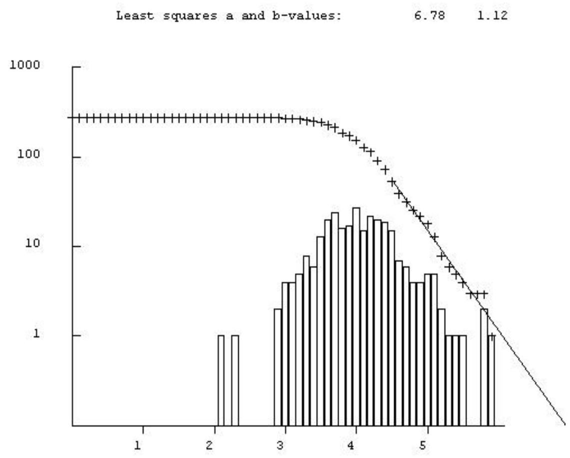

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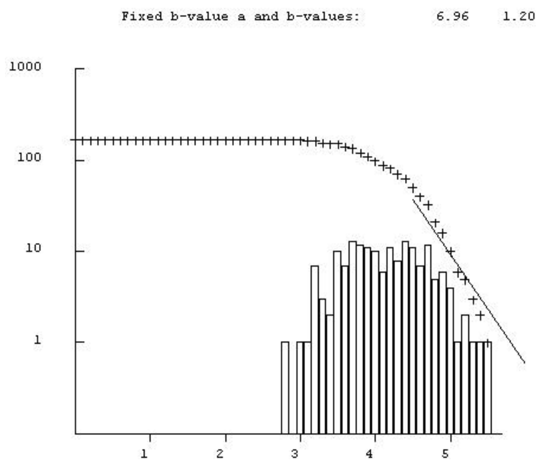

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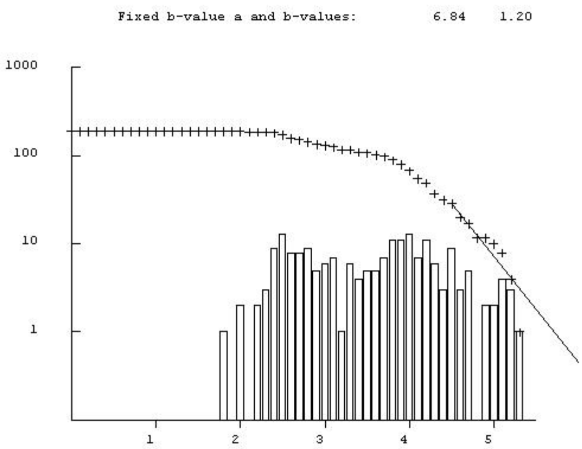

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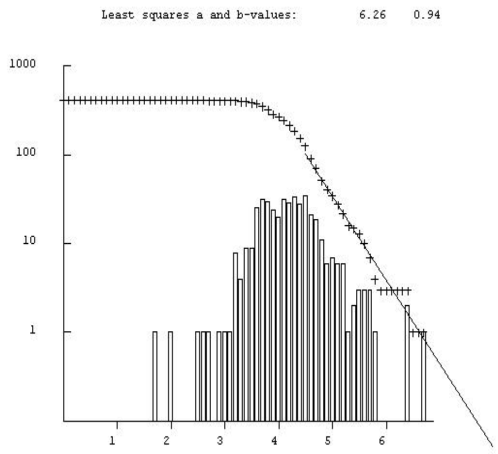

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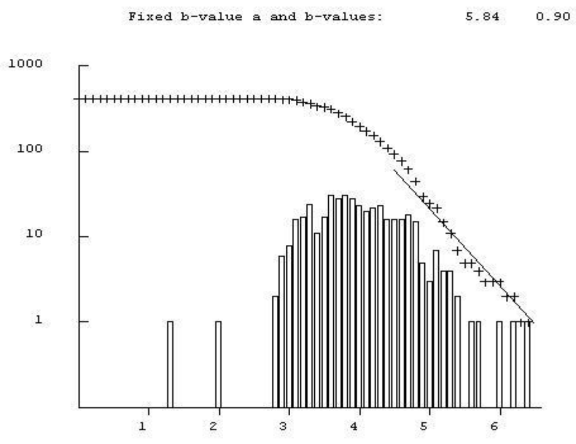

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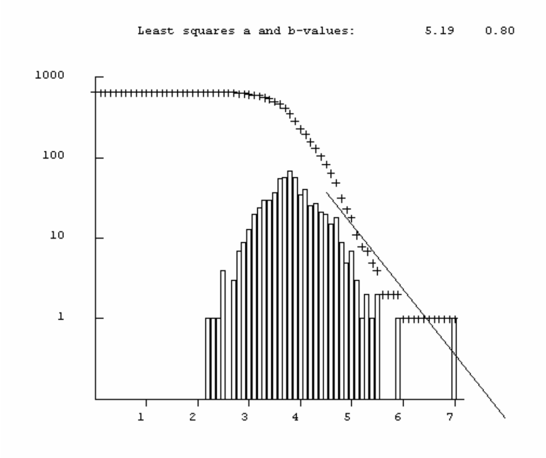

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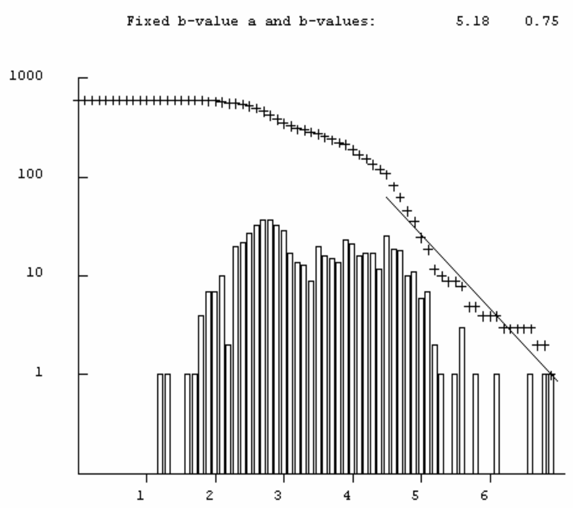

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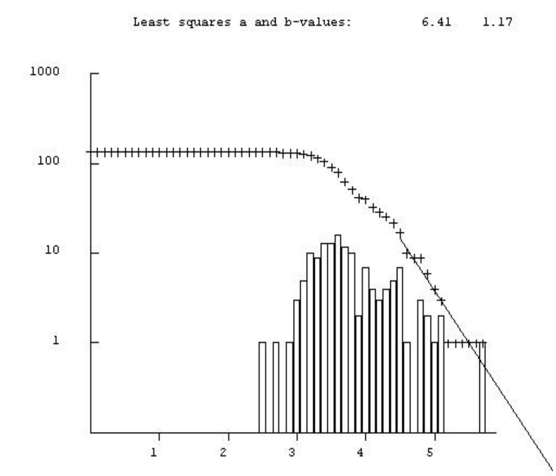

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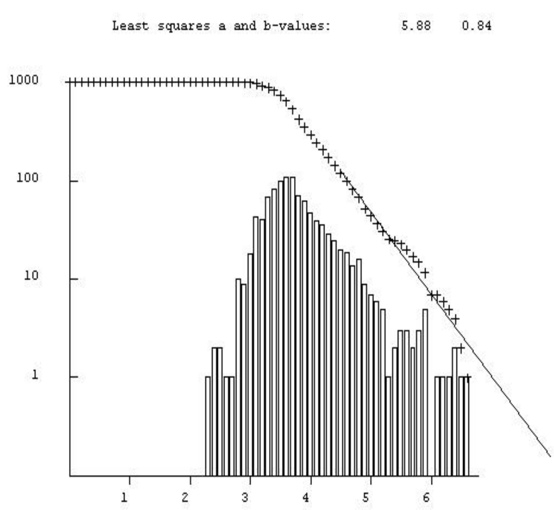

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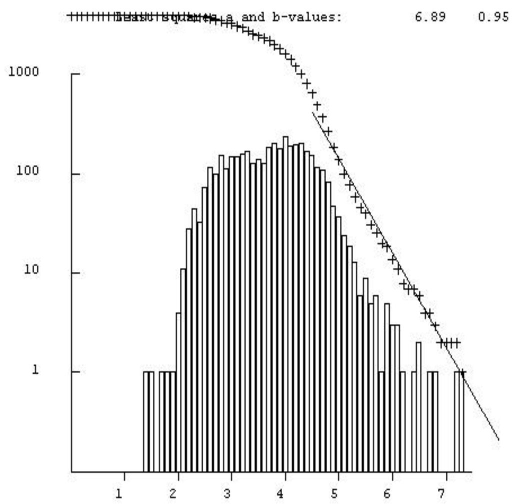

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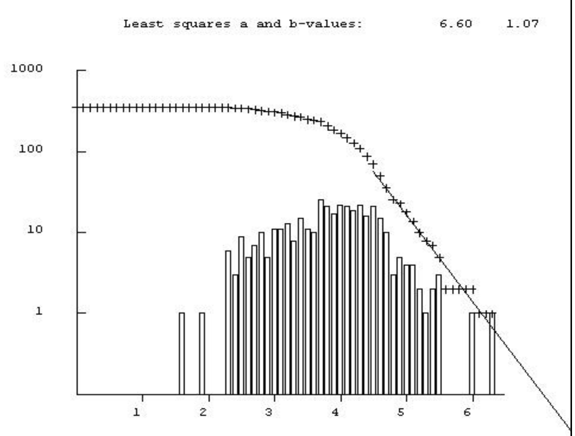

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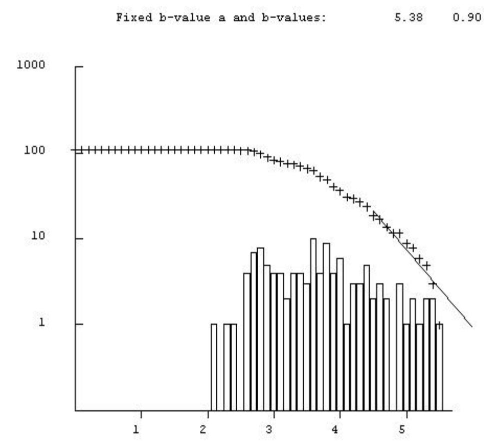


Zone 14

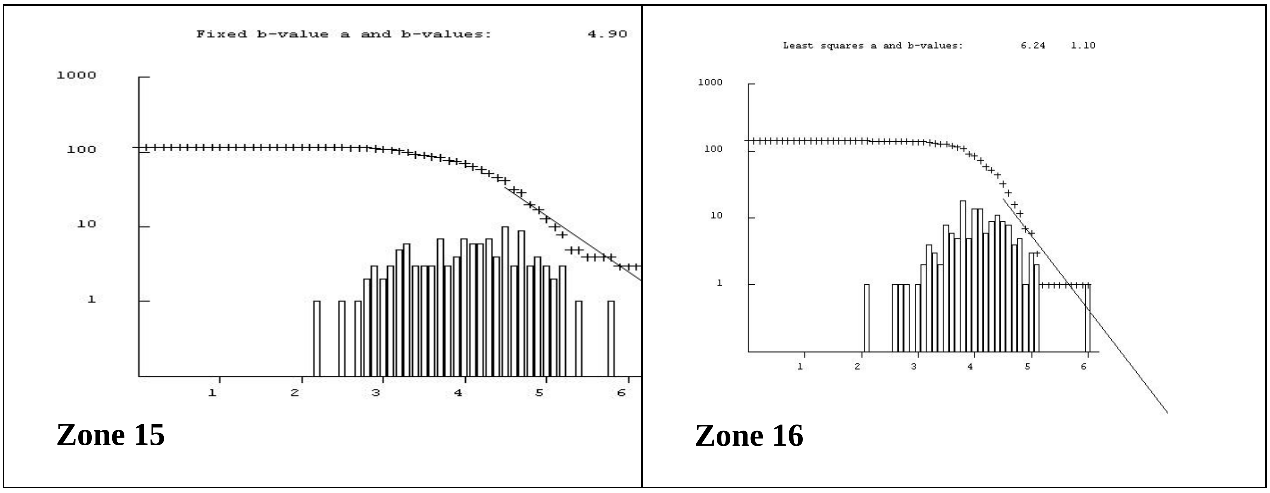


Figure.5.1. Magnitude-frequency distributions and recurrence regressions for the determination of ‘a’ and ‘b’ values for each of the zones. The recurrence relation has the form logN=a-bM, where ‘N’ is the cumulative number of earthquakes of or above a given magnitude, and where ‘a’ is expressing the seismicity level and ‘b’ is the slope of the curve. When used in a probabilistic seismic hazard analysis such relations are expressing the belief that the future will statistically be like the past.

Table 5.1(a,b) summarizes the regression parameters found for the sixteen zones. The maximum magnitudes observed were taken from the catalogue, which was prepared as explained earlier with the help of PMD, NORSAR, and other sources (notable ISC), and from international research papers regarding the seismicity of Pakistan. The activity values, a-value found by regression on each of the sub-zones together with the maximum observed magnitudes. There is also a zone 18 and a zone 19 that are deeper depth levels of zone 1 (Hindukush).

Table.5.1a. Recurrence parameters for each of the seismic zones. Zone 0 is a zone that comprises all of the other zones.

Zone	b-value	a-value	a-value (norm)	a-value (norm)	No of events
0	0.99	7.86	6.2067	6.2067	16657
1	0.94	7.27	5.8000	5.6167	76186
2	0.75	5.1	3.4467	3.4467	727
3	1.12	6.78	5.1267	5.1267	278
4	1.2	6.96	5.3067	5.3067	167
5	1.2	6.84	5.1867	5.1867	192
6	0.94	6.26	4.6067	4.6067	420

7	0.9	5.84	4.3000	4.1867	420
8	0.8	5.19	3.5367	3.5367	653
9	0.75	5.18	3.6000	3.5267	607
10	1.17	6.41	4.7567	4.7567	136
11	0.84	5.88	4.2267	4.2267	1086
12	0.95	6.89	5.2367	5.2367	3938
13	1.07	6.6	4.9467	4.9467	362
14	0.9	5.38	4.0000	3.7267	112
15	0.75	4.9	3.2467	3.2467	119
16	1.1	6.24	4.5867	4.5867	145

Table 5.1b … continued.

Zone	Obs. M_{max}	Model M_{max}	Lambda(λ)	Beta(ß)	Model ret. per. (M6)	Obs. ret. per. (M6)	Events > M6
0	7.7		28.4962	2.2794	0.5410	0.1285	350
1	7.6	8.0	19.4088	2.1643	0.6918	0.1898	237
2	7.7	8.0	0.7027	1.7268	11.3034	15.000	3
3	5.9	7.0	0.5633	2.5788	39.1933	-	-
4	5.5	7.0	0.3521	2.7630	78.2010	-	-
5	5.3	6.5	0.2671	2.7630	103.0890	-	-
6	6.7	7.6	1.2439	2.1643	10.7947	11.2500	4
7	6.4	7.0	0.9549	2.0722	12.5892	7.5000	6
8	7.0	7.3	0.4974	1.8420	18.3321	45.0000	1
9	6.9	8.0	1.0000	1.7268	7.9432	4.5000	10
19	5.7	7.0	0.1382	2.6939	183.3211	-	-
11	6.6	7.6	1.5659	1.9341	6.5044	1.8000	25
12	7.3	7.6	4.7510	2.1873	2.9054	0.8035	56
13	6.3	6.8	0.6468	2.4636	29.7312	150000	3
14	5.5	7.0	0.4786	2.0722	25.1188	-	-
15	6.4	7.0	0.4433	1.7268	17.9148	11.2500	4
16	6.0	6.5	0.2026	2.5327	103.0890	450000	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 areas where there are not enough local strong motion data to support the development of indigenous relations. The most important factor here is the epistemic 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 uncertainty there is also an epistemic uncertainty that expresses our lack of knowledge. In PSHA models this may be 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 General Review of Models

One complicating factor in the present study 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 few relations for the Himalaya region.

There are PSV relations available for:

- <u>Transcurrent or strike-slip regimes</u> (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).
- <u>Subduction zones</u>, including 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.
- <u>Extensional regimes</u>, 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.
- <u>Intraplate regions</u> (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.
- <u>Compressional tectonics</u>, where little 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 is 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 spectral relation of Ambraseys et al. (1996) among the possible relations, based on the fact that the tectonics is largely compressional also in the region where the Ambraseys et al. (1996) data come from.

There is, however, a new spectral relation available now that may be a possible alternative, namely one by Sharma and Bungum (2006) based on a combination of available Himalayan data and supplementary European data for near-field distances where the Himalayan data are not sufficient. This relation is discussed in more details below.

6.2 Some Selected Models

The following ground motion models have been considered:

1. Ambraseys et al. (1996), spectral. Based on 422 horizontal records in the magnitude range 4.0 to 7.9 and distance range 0–260 km.
2. Sharma (1998), PGA only. 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), PGA only. 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), PGA only, Iran. Based on 160 horizontal records in the magnitude range 3.4-7.4 in the distance range from 0-180 km.

5. Sharma and Bungum (2006), spectral. Based on 175 strong-motion records from 12 Himalayan earthquakes since 1986 with moment magnitudes 4.5-7.2 and hypocentral distances in the range 10-200 km, supplemented with additional data for near-field distances from a European data set of nine reverse-faulting earthquakes in the magnitude range 6.0-7.2.

The Khademi relation is based on data from a presumably compressional regime (not specified regions in Iran), but demonstrate unexpected low attenuation. The predicted accelerations from this relation are extremely high at all magnitudes and distances, indicating also a low scaling with increasing magnitude. This calls for caution.

The Sharma (1998), Jain et al. (2000) and Sharma and Bungum (2004) relations have the advantage of being developed from Himalayan data, but unfortunately only the last one is a spectral relation. The Jain et al. (2000) relation is largely based on data from SRR (Seismic Response Recorder) sensors, which have quality problems, and sources are not confined to the Himalayan region. The Sharma (1998) relation is largely replaced by the new Sharma and Bungum (2006) relation, which moreover is developed both for rock and soil conditions.

This leaves us essentially with a choice between the Ambraseys et al. (1996) relation and the new Sharma and Bungum (2006) relation. The first one is well proven and tested while the latter has not been tested before in practical use, leaving more uncertainties. Figs. 6.1 and 6.2 shows in this respect a comparison between the two models for magnitudes 7.0 and 5.0 at different frequencies.

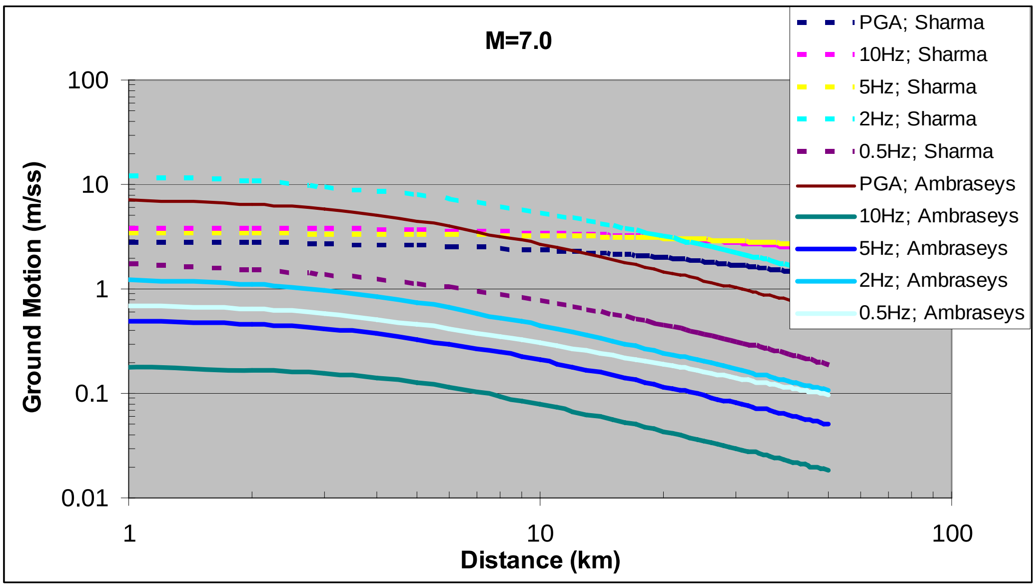


Fig. 6.1. Comparison between the Ambraseys et al. (1996) and Sharma and Bungum (2006) models for M 7.0 at different periods.

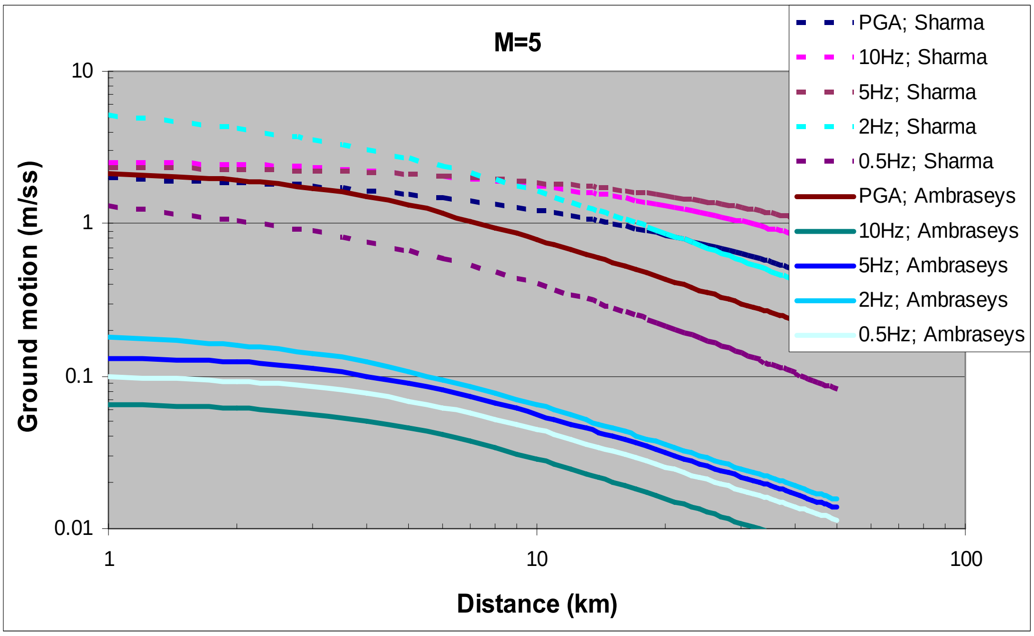


Fig. 6.1. Comparison between the Ambraseys et al. (1996) and Sharma and Bungum (2006) models for M 5.0 at different periods.

At the higher magnitude the two models are reasonably similar except that the Sharma and Bungum (2006) model does not fall off as sharply with distance, which is a recognized characteristic of Himalayan earthquakes. The models are, however, very different at M 5, which is still important for hazard at low return periods (100-500 years). Both models were tested with our source model, including a detailed deaggregation, and it was concluded that the difference in magnitude scaling resulted in M 5 levels that are difficult to support, driving the hazard in an unrealistic way. It was therefore decided to use the Ambraseys et al. (1996) model in this study.

7 Seismic Hazard Results

The hazard computations are based on the source model presented earlier and on the selected attenuation relation. The lower integration level for the computations has been set to magnitude 4.5.

Peak ground acceleration (PGA) and corresponding spectral acceleration has been computed using Crisis2003 (Ordaz, 2003) with parameters as shown in Table 7.1. The earthquake activity is assumed to follow a Poissonian (memory free) distribution. While this is often not true for a smaller region experiencing large earthquakes it is a generally valid assumption for larger areas and earthquake populations. The level of seismic activity is described by the log-linear recurrence (Gutenberg-Richter) relation, which in Crisis2003 is specified with slightly different parameter notations:

- The λ-value describes the number of earthquakes with magnitude greater than $M_{threshold}$ that is expected to occur each year within each sub zone.
- The ß-value is the natural logarithm of the 'b' parameter in the Gutenberg-Richter recurrence relation, describing the ratio of larger to smaller magnitude earthquakes.

Table 7.1. Parameters used in the Crisis2003 seismic hazard computations.

Parameter	Values
Origin of the grid	70°E & 32.5°N
Increment	0.5 degrees in latitude and longitude
Number of points	13 in both latitude and longitude
Spectral ordinates	PGA, 0.1, 0.2, 0.5, 1.0, 2.0 s
Intensity limits	20 intensities from 0.001 to 20 m/s^2
Spatial integration limit	250 km
Minimum triangle size	11 km
Distance/triangle size ratio	3
Return periods	100, 500, 1000, 2500, 5000 years
Magnitude integration threshold	4.5
Attenuation Relation	Ambraseys et al. (1996)

We tested the activity model with different spatial integration parameters as needed in Crisis2003. The recommended values of 11 and 3 were tested against other values as shown in Table 7.2. The results did not indicate significant difference between the selected values, and we proceeded by using the values of 11 km and 3.

Table 7.2. Selected Crisis 2003 tests with spatial integration parameters.

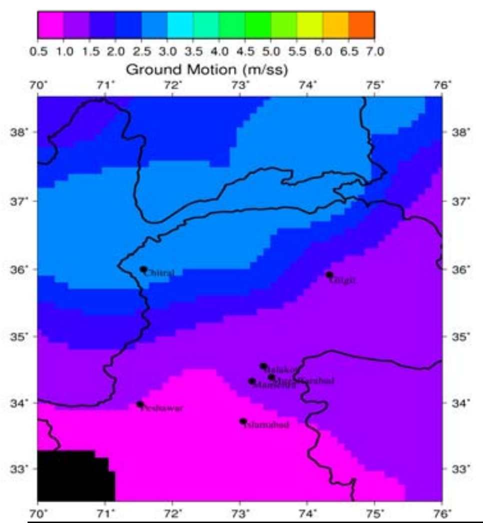
Test Point (lat, long)	▲11(km) ratio=3	▲5(km) ratio=3	▲5(km) ratio=4	▲0.5(km) ratio=4
Pt1(35,71)	3.88 m/s^2	3.88 m/s^2	3.87 m/s^2	4.3 m/sec^2
Pt2(33.71)	1.32 m/s^2	1.32 m/s^2	1.32 m/s^2	1.41 m/s^2
Pt3(33,74)	1.25 m/s^2	1.27 m/s^2	1.27 m/s^2	1.28 m/s^2
Pt4(35,74	2.24 m/s^2	2.24 m/s^2	2,43 m/s^2	2.45 m/s^2

The M_{max} (see Table 5.1) is the maximum magnitude that can be physically and tectonically accommodated in region (this should not be mixed with what is probable for the region). The PSHA methodology integrates all ground motion contributions from a lower M_{lim} value (here set to 4.5, through engineering considerations) to the highest M_{max} value, in addition to looping through all source regions that could influence a particular site.

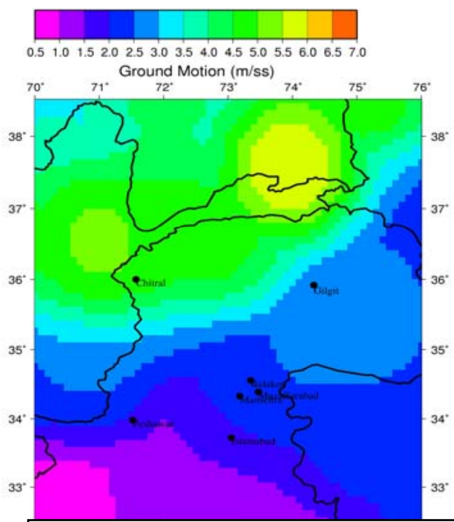
The results in Figs. 7.1 are presented after passing them through the GMT software. The ground motion values for each return period in each point are resampled from 0.5 to 0.1 degree and spatially low pass filtered by selecting the largest value within a 100 km diameter.

The seismic hazard zonation plots show, as expected, how the Hindukush region dominates the seismic hazard. For 500 year return period the city of Chitral is expected to experience PGA ground acceleration up to 4.5 m/s^2, whereas the city of Islamabad falls in a region of less than 2 m/s^2 ground shaking for the same annual probability. This exemplifies that the northern regions are very dynamic in terms of the seismic hazard levels.

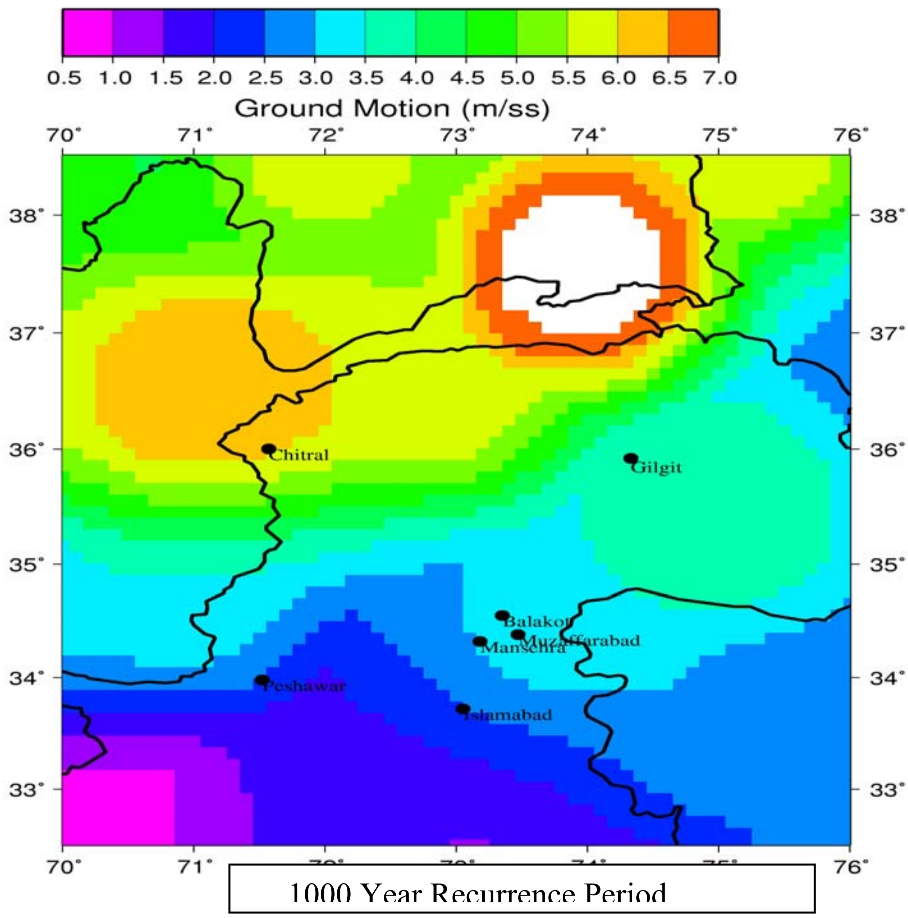
Equal hazard (computed independently from the different spectral ordinates in the applied ground-motion relation) elastic response spectra were developed for selected cities as shown in Fig. 7.2. The spectra are scaled to the PGA values in Fig. 7.1.



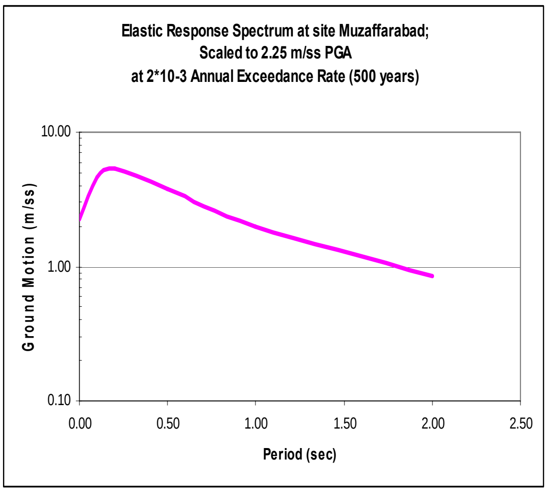
100 Year Recurrence Period

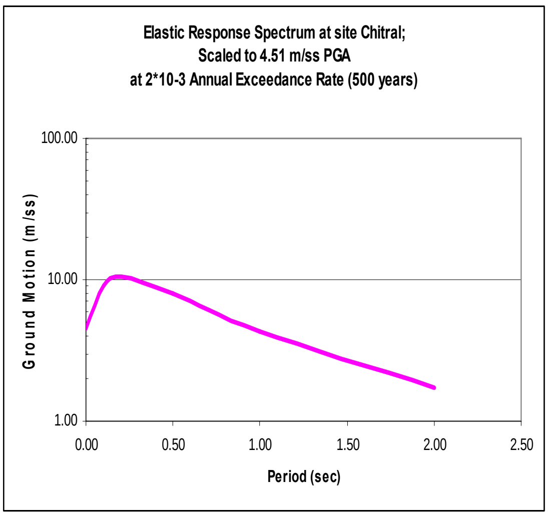


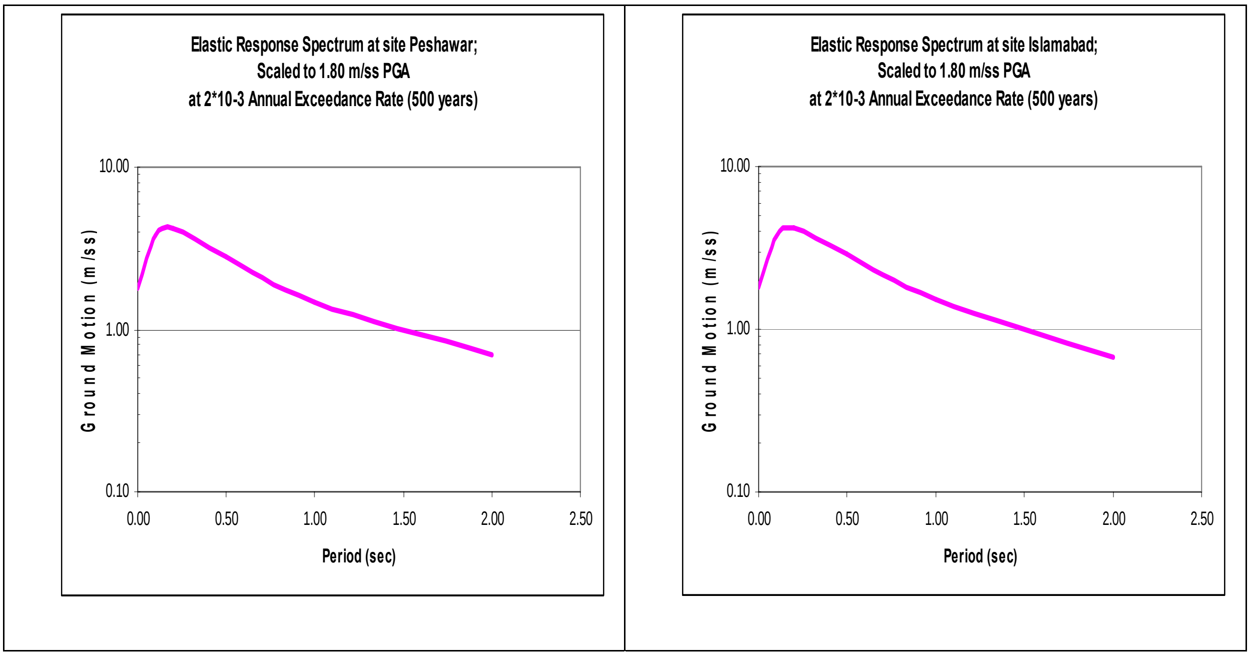
500 Year Recurrence Period



Figures.7.1 Hazard maps for return periods of 100 (upper left), 500 (upper right) and 1000 (lower) years. Results for rock sites.







Figures.7.2 Equal hazard elastic response spectra developed for the cities Islamabad, Muzafarrabad, Peshawar and Chitral. Results are for rock sites, and soil amplification will change the spectral shapes. Note that the spectra have been scaled to the PGA levels in Fig. 7.1 (for annual exceedence rates of 500 years).

8 Discussion

The results obtained in the present study for 500 years return period can be compared with the GSHAP results in Fig. 8.1 (Giardini et al., 1999) for 10% exceedance probability in 50 years, corresponding to 475 years. While the GSHAP study covered a larger area there are obvious differences in that the present results estimate relatively lower hazard values for the lowland regions (Islamabad and southwards) and higher values than the GSHAP study for the northernmost Hindukush areas. This is a commonly observed difference between a regional and a global study, since the latter cannot be as detailed in the source zonation. In view of hazard results from other parts of the Himalaya we regard the results obtained for the Hindukush area as somewhat higher than would normally be expected.

One main basis of PSHA computations is the historical earthquake catalogue for the region under focus. For northern Pakistan (as for large parts of the Himalaya) the current catalogues are largely incomplete and uncertain in magnitude and epicentre estimates when we go back in time. This uncertainty and incompleteness in the historical records reflects into an uncertainty of the computed hazard results and represent a major challenge. Furthermore, there is still a long way to go with respect to understanding (and thereby predicting in more detail) the tectonic processes in this region, which is more complicated than in most other regions of the world.

The conducted study represents a first step towards estimating seismic hazard for northern Pakistan, and the team has experienced the need for continuing the efforts started, and a continuation of the present work is already planned for. The planned work may result in some change of the hazard levels computed in the present study.

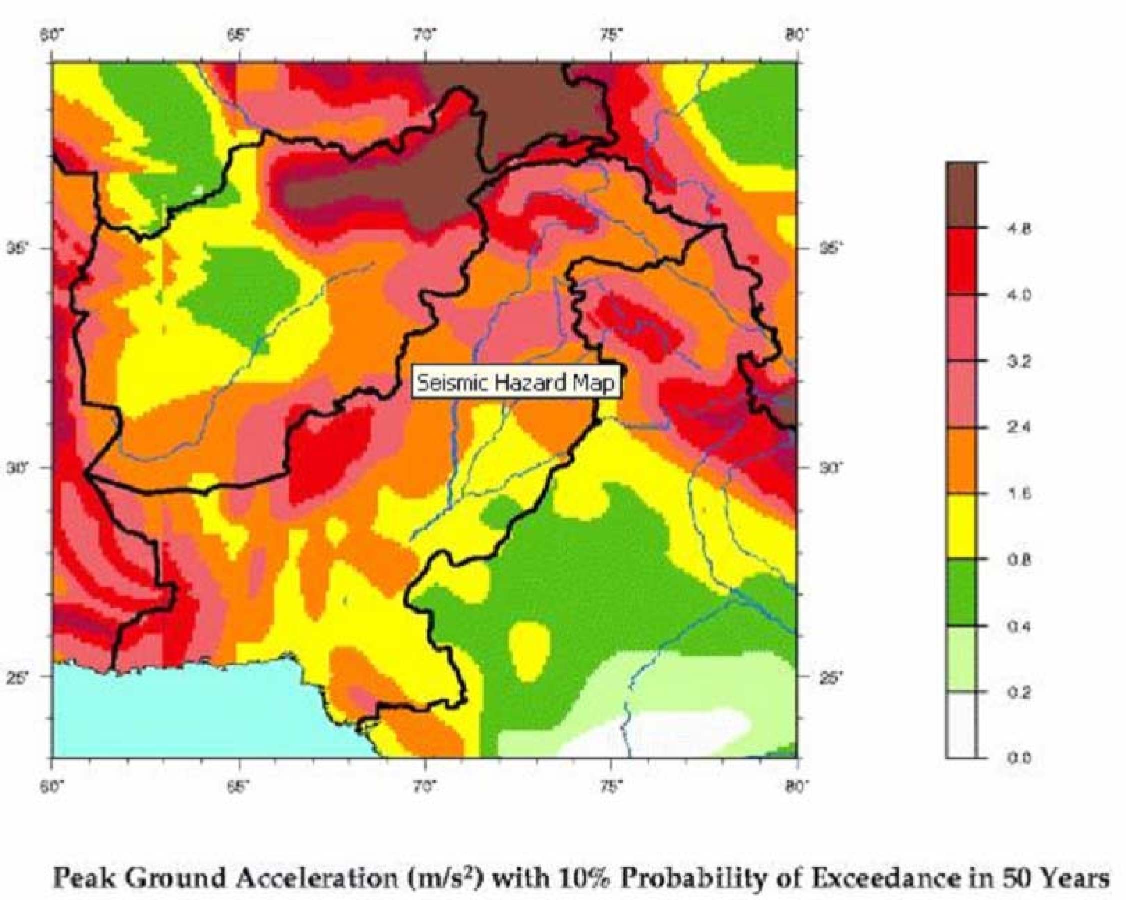


Fig. 8.1. GSHAP (Global Seismic Hazard Assessment Project) seismic hazard results in and around Pakistan (Giardini et al., 1999).

9 References

Ambraseys, N. and R. Bilham (2000). A note on the Kangra M_S = 7.8 earthquake of 4 April 1905. *Current Science*, 79(1), 45-50.

Ambraseys, N.N. and J. Douglas (2004): Magnitude calibration of north Indian earthquakes. *Geophysical J. Int.*, 159, 165-206.

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.

Armbruster, J., Seeber, L. & Jacob, K. (1978): The northern termination of the Himalayan front: active tectonics from micro-earthquakes. *J. Geophys. Res*. 83, 269-282.

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 ground motion relations. *Seism. Res. Lett*., 68, 24-40.

Bhatia S., M.R. Kumar and H.K. Gupta (1999): A probabilistic seismic hazard map of India and adjoining regions. *Annali di Geofisica*, 42(6).

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

Bommer, J.J., F. Scherbaum, H. Bungum, F. Cotton, F. Sabetta and N. A. Abrahamson (2005): On the use of logic trees for ground-motion prediction equations in seismic hazard analyses. *Bull. Seism. Soc. Am*., 95(2), 377-389.

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 *Computers 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.

Chander, R. (1988): Interpretation of observed ground level changes due to 1905 Kangra earthquake, Northwest Himalaya. Tectonophysics 149, 289-298.

Chatterjee, S.N. (1992): Micro earthquakes survey and seismicity of northwest Himalaya. Himalayan seismicity, Gupta, G.D.ED., Geol. Soc. India 23, 23

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.

Fujiwara, S., M. Tobita, H.P Sato, S. Ozawa, H. Une, M. Korai, H. Nakai, M. Fujiwara, H. Yarai, T. Nishimura and F. Hayashi (2006): Satellite data gives snapshot of the 2005 Pakistan earthquake. *EOS Transactions AGU*, 87 (7), 73,77.

Giardini D. et al. (1999): Global Seismic Hazard Assessment Program (GSHAP). http://www.seismo.ethz.ch/GSHAP/global/.

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

Khademi M. H. (2002): Attenuation of peak and spectral accelerations in the Persian Plateau. *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.

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*.

Molnar, P. and Taponnier. P. (1975): Cenozoic tectonics of Asia: effect of a continental collision. *Science*, 189: 419-426.

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. H. Khan, and R.D. Lawrence (1991), Active faults of Pakistan, map sheets and inventories, Spec. Publ. 21, 141 pp., Hiroshima Univ. Res. Cent. For Reg. Geogr., Hiroshima, Japan.

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

Ordaz, M., A. Aguilar and J. Arboleda (2003): Crisis 2003 Program for computing seismic Hazard, Ver. 3.01.

Seeber, L. and Armbruster, J., in Earthquake Prediction- An International Review (eds. Simpson, D. W. and Richards, P. G,), Maurice Ewing Series, Am. Geophys. Union, 1981, vol. 4, pp. 259-277.

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(4), 1063-1069.

Sharma, M and H. Bungum (2006): New strong ground-motion spectral acceleration relations for the Himalayan region. *Proc., 1st European on Conf. Earthq. Eng. and Seism.*, Geneva, 3-8 September 2006, Paper No 1459, 8 pp.

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

Thakur, V.C., V. Sharma, and A.K. Mundepi (2000): Seismicity of the great 1905 Kangra earthquake meizoseismal region in Kangra-Chamba, NW Himalaya. *Tectonophysics*, 326, 289-298

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.

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.

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

10 Glossary of Terms

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 travelled, 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 behaviour 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 kilometres. 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.

Epicentre - 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 kilometres. Relative movements across a fault may typically be tens of centimetres 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., land sliding, 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 kilometres 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 epicentre" 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 epicentre (< 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 Earthquake Engineering Research Institute, U.S (EERI) 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 framework (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 judgment 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 judgment 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 >0.1 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.

Seismotectonic - 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 interpolate 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.