6. SEISMICITY

6.1 GENERAL

Basic concepts about the approach followed to assess the seismic risk in a region of interest are presented. Some case studies are presented to illustrate how such works are normally carried out in practice.

The current status of seismic risk assessment is that no generally accepted method exists. However, some techniques have become part of standard practice. Therefore, emphasis has been given in this work to apply standard techniques aiming at a better understanding and acceptability of results.

6.1.1 SEISMIC EVALUATION - CONCEPTUAL FRAMEWORK AND METHODOLOGY

6.1.1.1 SEISMIC HAZARD, SEISMIC VULNERABILITY AND SEISMIC RISK

There seems to be some confusion in defining hazard and risk. Many people even consider the word *hazard* as a synonymous of *risk*, and both are found in the literature with subtle variations which result confusing.

The Earthquake Engineering Research Institute's Committee on Seismic Risk defines:

- *Seismic risk* as the probability that social or economic consequences of earthquakes will equal or exceed specified values at site, at several sites, or in an area, during a specified exposure time.

- *Seismic hazard* as any physical phenomenon (e.g. ground shaking, ground failure) associated with an earthquake that may produce adverse effects on human activities.

Man-made facilities constructed in seismic regions are subjected to earthquake hazards that are not under human control. If the facilities are seismically vulnerable due to their construction technique, then very likely are likely at a risk.

On the other hand, if the facilities are intentionally made less vulnerable or if they are inherently not vulnerable, then they are little affected by earthquakes and the seismic risk is low, even if the earthquake hazard is high. This means that while seismic hazard must be accepted as given by nature, seismic risk can be controlled and reduced by means of a correct application of earthquake engineering technique.

The seismic hazard analysis of a site is intended to identify the existing natural level of exposure in order that correct earthquake engineering measures can be implemented to keep the seismic risk at a reasonably low level in spite of the seismic hazard being moderate or high. The degree of protection of a facility can be relaxed or increased as a function of the actual seismic hazard level. This fact emphasizes the importance of a correct identification.

Seismic hazard assessments yield two types of results: general qualitative statements about the seismic exposure and specific quantitative parameters called seismic design parameters.

6.1.1.2 SEISMIC DESIGN PARAMETERS

The following paragraphs contain description of some of the most relevant seismic design parameters. These parameters have been derived in this study for the sites under consideration.

6.1.1.2.1 PEAK GROUND ACCELERATION (PGA)

This parameter represents the highest pulse of ground acceleration during an earthquake. Although it has some theoretical shortcomings as a statistically representative measurement of the intensity of an earthquake, it has been, and still is, the most widely used numerical assessment of the "punch" of an earthquake. Dozens of statistical relationships describing specific characteristics of an earthquake have been derived on the basis of PGA. These range from structural design parameters to damage statistics.

6.1.1.2.2 PEAK GROUND VELOCITY (PGV)

This parameter is less widely used than PGA; however, it has been gaining importance as a supposedly more stable statistical descriptor of the damaging capabilities or "punch" of an earthquake. Lately it has been used to scale empirical seismic velocity spectra which are then converted to acceleration spectra which, in turn, are used to evaluate seismic stresses in structural analysis.

6.1.1.2.3 DESIGN SPECTRA

These are used to calculate the seismic loading on structures. They can be used for the final structural design of all facilities in hydropower projects. Only very critical facilities (such as large dams) require more comprehensive ground motion descriptors. The response spectra would be sufficient information at the feasibility stage for virtually all aboveground facilities expected to be built on the analyzed sites. Once appropriately reviewed, response spectra would be one of the main tools for a final structural design.

6.1.1.3 DEGREE OF EARTHQUAKE PROTECTION

Due to the nature of the seismic loading, no facility can be made absolutely earthquake-proof. Modern technology offers "earthquake resistance", meaning that the facility is intended to survive a strong earthquake while undergoing a certain degree of damage. In fact, the very process of undergoing controlled damage and post-elastic deformations is one of the main sources of seismic energy dissipation, preventing the need of having to provide oversized members capable of handling the seismic energy in the elastic range of the structural materials.

This means that there is a range of possible solutions to earthquake resistance. There is a trade-off between having to build a larger structure, able to delay the onset of damage and accepting a lower threshold of damage (provided the structure is ductile enough as to dissipate the excess of seismic energy). In the latter case, although a well designed facility does not collapse, the damage incurred may put it out of commission temporarily - or even permanently in case of extreme ground shakings.

Hence, how low to accept the onset of damage is an economic and functional decision. It depends on the importance of the hydroelectric project and also on the importance of individual facilities within the project. This also means that not all facilities need to be designed for the same level of earthquake resistance.

To provide the adequate amount of earthquake protection two levels of seismic loading are often defined for important projects: Operating Basis Earthquake, and Maximum Credible Earthquake. Seismic designs are carried out using this limiting conditions and values in between. For the foregoing reasons, the seismic evaluations described in Section 6 assess a range of seismic loadings rather than specific values.

6.1.1.3.1 OPERATING BASIS EARTHQUAKE (OBE)

This is a seismic loading that a facility must withstand without loss of operating capabilities. It is associated with the onset of damage. The more important a facility is within a functional system, the higher the OBE should be. To decide how high the loading must be, an acceptable risk level must be decided upon. For example, an acceptable risk level associated with the onset of structural damage due to earthquake in an ordinary building is about 15 per cent probability of the load being exceeded in a 30 year period. This implies about 0.005 events per year or equivalently, close to a 200-year returns period. A tolerable risk level associated with the suspension of operations of a large and important dam should be much lower, say 5 percent in 100 years i.e. a 2000-year return period.

Of course tolerable risks of incurring significant damage must be even lower, say 1 percent probability in 100 years in the case of a very important facility; this is about 0.0001 events per year or equivalently, a 10000 year return period. But these low levels of probability are better handled with the concept of a maximum credible earthquake discussed in another section of this report.

6.1.1.3.2 RISK LEVELS

As discussed above, earthquakes are an uncertain loading. A significant earthquake may not hit a facility during its lifespan; if it does hit, its "punch" is not readily predictable. One can only attempt to correlate seismic load levels to probabilities of occurrence.

In the present seismic analysis, the earthquake loading corresponding to a number of hazard levels were evaluated for each site. Earthquakes were assessed for hazard levels of 0.005, 0.002, 0.001, 0.0005, 0.0002, and 0.0001 events per year (which is the same as return periods of 200, 500, 1000, 2000, 5000 and 10000 years. This approximately corresponds to the following probabilities of occurrence: 15% in 30 yrs, 10% in 50 yrs, 10% in 100 yrs, and 5%, 2%, 1% in 100 yrs.

To correlate the above mentioned probabilities of occurrence with a time period and a rate of occurrence, a Poisson random process is usually assumed. In accordance to the exponential distribution, the relationships are of the form:

$$P_{exc} = 1 - e^{\frac{T_e}{RP}} \qquad \textbf{(6.1)}$$

or conversely

$$RP = -\frac{T_e}{\ln(1 - P_{exc})} \qquad \textbf{(6.2)}$$

with:

RP = return period in years or average time between events
T_e =time interval during which facility will be exposed to seismic activity, i.e. lifespan
P_{exc} =probability of the seismic activity being exceeded during the time span Te

As well known in other disciplines of engineering, the return period is the expected period between events and thus is the inverse of the annual probability of occurrence, also known as the rate of occurrence (events/year).

In this regard, following criteria may be considered for the selection of design parameters:

- *Ordinary facilities* can be designed for seismic loading that has the probability of 20% of being exceeded in 50 years. This corresponds to a return period of approximately 225 years or a recurrence of 0.00446 events per year.(Hazard level A)
- *Special facilities* can be designed for seismic loading that has the probability of 10% of being exceeded in 50 years. This corresponds to a return period of approximately 475 years or a recurrence of 0.0021 events per year.(Hazard level B)

- *Essential facilities* such as hospitals, bridges, etc. can be designed for seismic loading that has the probability of 5% of being exceeded in 50 years. This corresponds to a return period of 975 years or a recurrence of 0.001026 events per year.(Hazard level C)

- *Critical facilities* may be designed for seismic events with even lower probability (i.e. 0.0001 or 10000 years return period).(Hazard level D)

6.1.1.3.3 MAXIMUM CREDIBLE EARTHQUAKE (MCE)

Rather than attempting to assess very low probabilities of occurrence, it is more pragmatic to evaluate an upper bound earthquake. This earthquake loading is thus assumed to be the worst possible earthquake intensity that can occur at the site. MCE's are normally evaluated for each site of interest.

6.1.2 GEOTECTONICAL CONSIDERATIONS

In the area of interest, major tectonic features should be identified. This information normally provides the basic framework to understand how the surface of the earth, as seen today, evolved to the present conditions. This assessment gives also important hints about expected future activity.

6.1.2.1 GLOBAL SEISMOTECTONICS

The present knowledge about seismic activity on global basis is summarized in Figure 6.1. Evidently, most of the events follow the borders of the earth crust's segments known as "tectonic plates". Figure 6.2 depicts the main plates and their direction of movement.

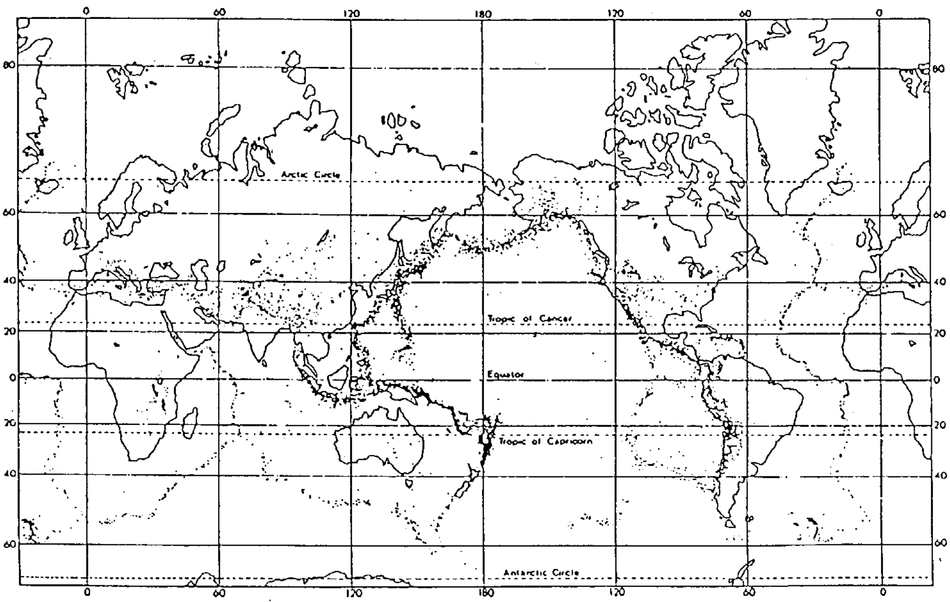

Fig. 6.1: **Seismicity map of the world**

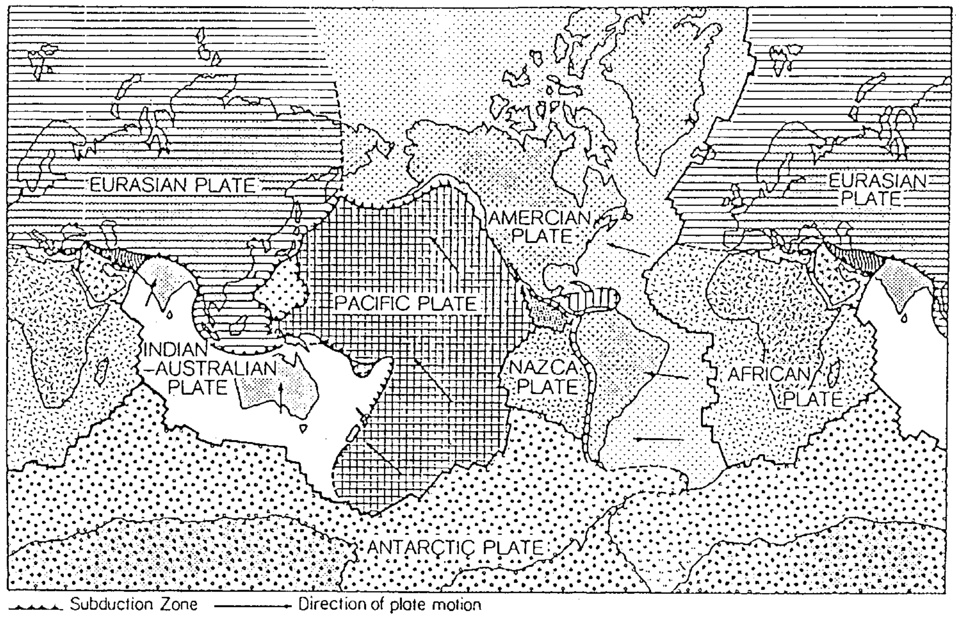

Fig. 6.2: **Tectonic plate map of the world**

Boundaries of plates are of four main types:

a) *Divergent zones,* where new plate material is added from the interior of the earth. These are found at the oceanic sea floor ridges.

b) *Subduction zones*, where plates converge and the under thrusting one is consumed. A typical example is the west coast of Central and South America.

c) *Collision zones*, former subduction zones where continents riding on plates are colliding. Typical examples are the Himalayas and the Alps.

d) *Transform faults*, where two plates are simply gliding past one another, with no addition or destruction of plate material.

Almost all earthquakes closely follow plate boundaries and are related to relative movements of the plates.

Besides the roughly 15 main plates already identified, smaller sub-plates or buffer plates exist which in some areas tend to ease the relative movement of larger plates. Buffer plates have been identified in Tibet and China, in the western USA and in the junction of African, Arabian, Iranian and Eurasian plates.

On the other hand, plates are not rigid bodies, as could be understood form previous description. Intra-plate earthquakes, not associated with plate boundaries, also occur. These makes the analysis of earthquake sources more complex, especially when these are not clearly defined.

6.1.2.2 ASSESSMENT OF REGIONAL SEISMOTECTONICS - AN EXAMPLE IN THE HIMALAYAS

The Himalayas originated from the collision of the Indian tectonic plate with the Eurasian plate. The Indian-Australian Plate, drifting to the north, has rammed into the southern flank of the Eurasian Plate. The collision of the two plates began about 50 million years ago. The full contact between the two plates was completed about 40 million years ago. Since that period the Indian plate has kept on drifting northward, acting as a rigid body which penetrates below the Asian plate. This intercontinental collision has resulted in intense deformation giving rise to complex folding involving thrust faulting and crustal thickening expressed as a series of thrust faults accompanied by a continental subduction process.

While the Indian plate is subducted under the Asian plate, its top has been "peeled off" and folded back. This has resulted in the production of a crustal accretion wedge, today known as the Himalayan Ranges. The accreted wedge significantly differs from the mantle since it is made up of continental crust and is separated from the former by a general plane of "decollement".

This tectonic process is the origin of the seismicity along the Himalayas and in particular in the northwestern corner of the Indian tectonic plate where Northern Pakistan and Kashmir are located. The geology in this corner of the plate is very complex and a biaxial state of stresses in the crust has created sharp bends and closed arches of faults called syntaxes.

In the region of interest the "decolled" accreted wedge includes a number of large thrust planes, two of them being the Main Central Thrust (MCT) and the Main Boundary Thrust (MBT). These thrusts split into a number of branching faulted planes known as the Hazara thrust system in the vicinity of an impressive syntaxial bent called the Hazara Syntaxis. Two of the sites of interest - the Neelum-Jhelum locations - are located within the syntaxis. All four sites, including Kotli and Allai-Khwar, lie on a structural block delineated by the previously mentioned MCT, the MBT and a third major feature called the Main Mantle Thrust (MMT). This block corresponds to the upper part of the Lower Himalayas, comprising mainly Eocambrian clastic sediments with limestone and quartzite mostly altered to phyllites and meta sediments. The MCT, which is a series of contiguous faults also, represents the geologic boundary between these Lower Himalayas and the Higher Himalayas on the north. The Higher Himalayas and the overlying Tibetan Tethys overthrust the Lower Himalayas along the MCT. The Main Mantle Thrust (MMT) passes in between MCT and MBT. Associated with it are rocks typical of higher-pressure metamorphism. The trace of this major overthrust appears to loop around the huge Nanga Parbat gneiss dome whose summit rises more than 8000 meters above sea level.

The Main Mantle Thrust separates the Indian Mass from the Kohistan Island Arc of Tahirkheli et al; this is, in turn, separated on the north from the Asian Mass by another megashear, the Northern Megashear. According to a newer tectonic model, there exist two suture zones indicated by the two megashears: the Northern Megashear and the Main Mantle Thrust. A chronological summary of the major tectonic episodes may be given as follows:

- Subduction of the Indo-Pakistan plate under the Kohistan Island Arch (upper cretaceous - Eocene).
- Suturing by two events; first the Eurasian continent under thrusts the Kohistan Arc along the Northern Megashear (NM), second the Indian Mass underthrusts the Kohistan Arc along the MMT (upper Cretaceous - Eocene)
- Formation of the Nanga Parbat Haramosh (Oligocene-Miocene).
- Creation of the Main Boundary Thrust (Pliocene).

The Lower Himalayas exhibit a peculiar structural pattern consisting of two northward projecting loops or re-entrants, the larger Hazara-Kashmir Syntaxis and the smaller Indus re-entrants, connected by a broad arc called the western arc. Around the Hazara-Kashmir Syntaxis, the regional trends curve a full 90° from the southeast-northwest trend of the Himalayas to the east-northeast trend of the Salt Range. Locally, individual faults can be traced throughout sharp arcs, some nearly 180°.

The development of the Hazara-Kashmir Syntaxis is known to have continued into post-Miocene time because the Murree formation is present in its axial zone. The Hazara-Kashmir Syntaxis is truncated by a younger N-S trending strike-slip fault called the Jhelum Fault. Precambrian to early

Paleozoic rocks wrap around the syntaxis like a horseshoe. These rocks overthrust mostly Mesozoic rocks along the MCT (on the eastern flank of the syntaxis) and along the northernmost faults of the Hazara thrust system (on its western flank). The mesozoic rock overthrusts early tertiary rocks along the MBT, which, in turn, overthrust the thick young tertiary sediments (Siwaliks) along another major thrust, the Himalayan Frontal Thrust (HFT).

6.1.2.3 FAULTING

As indicated by Dowrick (1988), faults are usually the seat of damaging earthquakes and therefore need to be given special attention. In this regard, following aspects need to be taken into consideration:

6.1.2.3.1 LOCATION OF ACTIVE FAULTS

Faults may be easier to identify in competent soils, when shallow earthquakes occur and the fault planes will reach the surface. However, this is not always in case of deep foci earthquakes and/or when the overburden is not stiff enough to allow rupture. In other cases faults may reach the surface but are difficult to recognize.
In general, following factors may complicate identification of faults:

- Low degree of fault activity.
- Erosion and deposition rates that are higher than fault slip rate.
- Dense vegetation covering faults.
- Dispersed fault zones at the surface so that individual features are less pronounced.

The location of active faults is normally shown on geologic and geotectonic maps. However, due to the above given reasons this information tends to be incomplete. Once way to partially overcome this problems is to study available published literature for the areas of interest. Therefore, identification of active faults may comprise the study of geologic and geotectonic maps, published literature, technical reports, photogeology, satellite images, etc. These studies may need to be complemented with fieldwork.

6.1.2.3.2 TYPES OF FAULTS

The characteristics of strong ground motions are strongly influenced by the type of faulting. Housner recommends that following four types of faults should be considered:

- *Low angle, compressive underthrust faults*. Result from tectonic sea bed plates spreading apart and thrusting under adjacent continental plates.(Fig.6.3, a)

- *Compressive, overthrust faults or reverse faults*. Compressive forces cause shearing failure forcing upper portion upwards.(Fig. 6.3, b)

- *Extensional faults, or normal faults.* Is the inverse of the previous type, extensional strains pulling the upper block down the sloping fault plane.(Fig. 6.3, c)

- *Strike-slip faults*. Relative horizontal displacement of the two sides of the fault take place along a essentially vertical fault plane (Fig. 6.3, d). These faults can also be subdivided in accordance with at least two criteria, i.e. inclination of fault plane and its constellation to bedding.

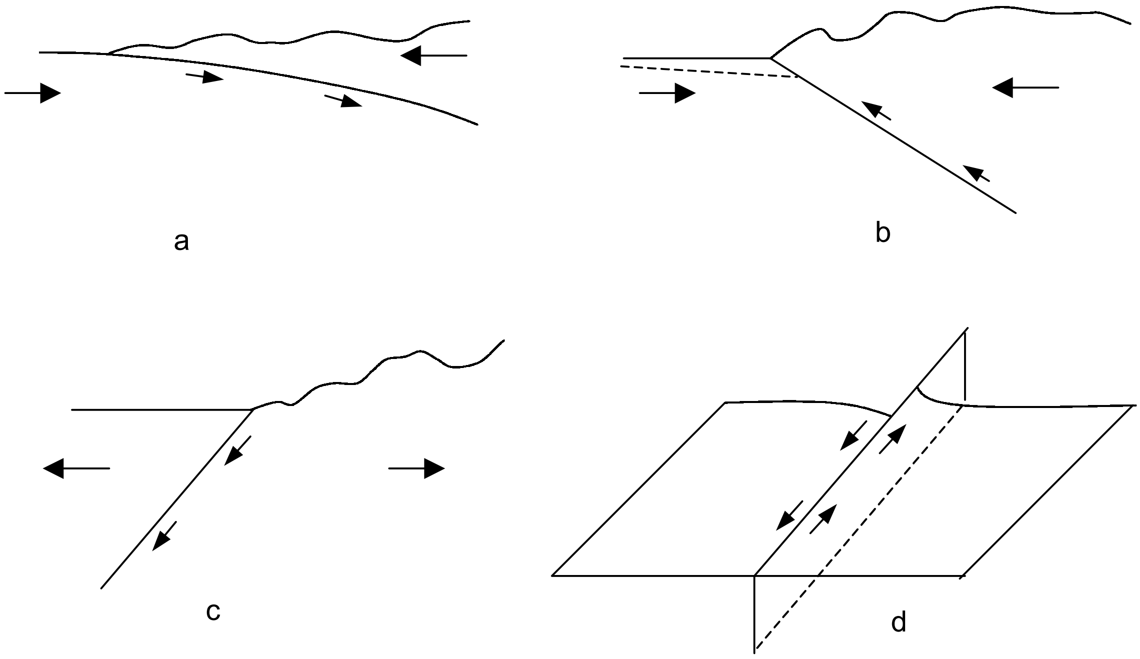

Fig. 6.3: **Main Fault Types**

Low angle, compressive thrust faults exist in global dimensions only, while other three types can have any size (from micro to continental). Movements along fault planes can have all combinations, ranging from 100% horizontal and 0% vertical to 0% horizontal and 100% vertical.

6.1.2.3.3 DEGREE OF FAULT ACTIVITY

As active faults are denoted every type of faults which are considered capable of moving in the future. Due to the fact that amount and frequency of movements can vary widely, it is important to have an estimate of the degree of activity likely of any fault in the region of interest. Various schemes have been proposed for this purpose, however, certain degree of uncertainty always exists, especially when the faults have not shown any activity in recent time or information about their activity is not available.

6.1.2.3.4 RELATIONSHIP BETWEEN FAULT AND EARTHQUAKE MAGNITUDE

It is always required to know the strength of earthquakes which can be generated by a given fault. However, this is a very difficult task. Therefore, some terms such as 'maximum credible earthquake' or 'safe shutdown earthquake (mostly applicable to nuclear power plants)' have been adopted to get at least an idea of order of magnitude of expected events.
Following methods are frequently used to estimate earthquake magnitude on basis of geological conditions:

a) *Magnitude vs. fault rupture length*. Is currently the most common method. Various relationships for different fault types have been derived, mainly using information on inter-plate zones.

b) *Magnitude vs. fault rupture area*. Used due to a recently recognized complication related to the occurrence of multiple events caused by two or more faults producing overlapping ground shaking. These events may appear superficially as one event, increasing the difficulty of assigning magnitudes.

c) *Magnitude vs. fault displacement*. Some relationships have been derived, however estimates are very rough due to the limited data available on true displacements.

Besides fault characteristics, an important aspect to consider it that the average rupture length of mid-plate events is much shorter than for those events located near the plate boundaries. Therefore, proper care should be taken when assigning magnitudes in these cases.

6.1.2.4 EFFECT OF SITE CONDITIONS

Besides the evaluation of local soil condition on the ground motion, also the influence of seismic activities on the following items should be considered:

a) Landslides
b) Mudflows
c) Liquefaction of non-cohesive soils
d) Failure of sensitive or quick clays
e) Land subsidence
f) Dam failure
g) Water waves, which may be caused by ground motion, landslides, dam failure, etc.

The assessment of the conditions at site should consider the determination of geological setup, especially with regard to:

a) Soils, including loose sediments transported by wind, water and/or gravity
b) Loose bedrock, chemically or physically weathered and /or totally disintegrated rock with no transport.
c) Bedrock

In this regard, some of most important effects of soil conditions and local geological features are discussed below:

- The greater the horizontal extent of softer soil, the less will be boundary effects (L1 or L2 in Figure 6.4).
- The depth (H1 or H2 in Figure 6.4) of soil overlying bedrock affects the dynamic response, increasing natural period of vibration of soil with increasing depth.
- Slope of soil strata lying on bedrock affects dynamic response.
- Topography of soil strata and bedrock affect incoming seismic waves, creating refraction, reflection, focusing and scattering.
- Local faulting and its characteristics need to be carefully evaluated.
- Soil types and their condition influence the response of the site and structures on it.
- Petrography, stratigraphy and exposure.

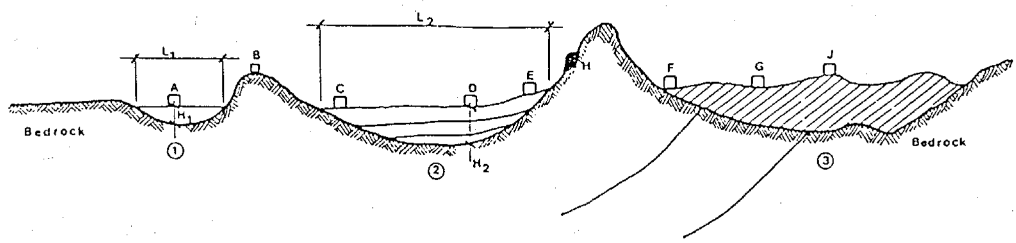

Fig. 6.4: **Schematic diagram showing different geological and soil conditions**

6.2 CASE STUDY - NORTH PAKISTAN

6.2.1 FAULTS IN THE REGION

With respect to the region of interest in the northern areas of Pakistan, several faults were located. These are briefly described in the following paragraphs.

6.2.1.1 MAIN BOUNDARY THRUST

It is a well-defined thrust fault (Murree Thrust of Wadia) between the molasses of the Murree Formation and metamorphic rocks. In the Kashmir region it follows a northwestern trend dipping towards northeast. It takes a sharp turn towards west then southwest along the Hazara Kashmir Syntaxis. In the Hazara area below the Panjal Thrust, the Main Boundary Thrust is not a well-defined tectonic feature. It constitutes an imbricated thrust zone of Precambrian to Cenozoic rocks, which may be called the Main Boundary Thrust Zone (MBTZ).

6.2.1.2 HIMALAYAN FRONTAL THRUST

It is a thrust fault roughly parallel to MBT trending NW direction with dip towards northeast. It separates the early Tertiary rocks (Murree Formation) from the thick young Tertiary sediments (Siwaliks). It passes very close to the Kotli dam site. Both the MBT and HFT are truncated by the Jhelum fault in the syntaxial area.

6.2.1.3 JHELUM FAULT

It is a left-lateral strike-slip fault which runs nearly in N-S direction with steep dip towards the east (Shahid Baig et al). In the Kashmir region the Jhelum Fault truncates the MBT, the Panjal Thrust and the Himalayan Frontal thrust.

The Jhelum fault is a younger fault and shows a left lateral offset of about 31 km along the western limb of the syntaxis as indicated by quaternary terraces which are uplifted and tilted, as exposed along the Jhelum, the Soan and the Kunhar rivers. (Shahid Baig et al).

The fault extends from the Soan valley to the Kaghan valley where it joins the shear zone of Bossart (Bossart et al.,1984) and extends towards the Allai-Kohistan. There is a strong possibility that the Jhelum fault cuts the MMT in the Allai-Kohistan towards Choar plains. The Jhelum fault may be one of the surface ruptures of the Indus-Kohistan seismic zone of Seeber and Armbruster (1979).

6.2.1.4 MAIN MANTLE THRUST

The Main Mantle thrust is at the collision front between the Indo-Pakistan and Cimmerian blocks. It extends west from Ladakh to northern Pakistan and eastern Afghanistan. The collision of the Indo-Pakistan block and the Kohistan Island arc is at least as young as Paleocene. However, fission track dates of the rocks along the Main Mantle Thrust have shown that its last movement is as recent as 15 Ma ago (Zeitler et al., 1982).

6.2.1.5 PANJAL THRUST

It is a thrust fault that in the Kashmir region runs along the Pir Panjal range (in the Kashmir region) in northwestern direction, roughly parallel and close to the Main Boundary Thrust which runs south with dip towards northeast. There is a thick sequence of Panjal Volcanics (upper carboniferous) exposed along the Pir Panjal range between Panjal thrust and the Main Boundary Thrust. Towards north of this fault are Precambrian met sediments of the Salkhala Formation. The thrust takes a sharp turn along the Hazra Syntaxis in harmony with the MBT. In the Hazara area it differs in both tectonic and stratigraphic setting, while it takes a southwestern trend. The low grade Precambrian Tanol Formation and the paleozoic rocks of the Tarbela-Peshawar terrain are thrust south on to unmetamorphosed rocks of Cambrian to Jurassic age in the Hazara area.

6.2.1.6 HAZARA THRUST

The Hazara thrust is structurally above the Margala Thrust, and emplaces rocks of Precambrian to Cenozoic age over rocks of mesozoic to Cenozoic age. On the southwest of the Hazara Kashmir Syntaxis, in the Hazara area, this is the first fault that places low-grade metamorphic rocks onto unmetamorphosed mesozoic to Cenozoic rocks further south.

6.2.1.7 MARGALA THRUST

The Margala thrust is structurally below the Hazara thrust and separates the Murree and Siwalik molasses of oligocene to pliocene on the south from eocene and older rocks on the north in the Margala and Kalachitta Hills. It is the northernmost boundary of the Murree and Siwalik molasses in the northern Potwar Basin of Pakistan.

6.2.1.8 NEELUM LUAT AND BARIAN (NLB) THRUST

There are three roughly parallel thrust faults striking in SE-NW direction with a dip towards NE direction. These are the northern part of the Kashmir Foreland fold-and-thrust belt (Shahid Baig et al). These are developed within the Precambrian met sediments belonging to the Salkhala Formation.

6.2.1.9 KOTLI FAULT

This fault is probably recent; it may be a strike-slip fault following a NNE-SSW direction observed between the Jhelum fault to the south and the HFT towards North. It is developed within the younger tertiary rocks of Siwaliks.

6.2.2 SITES

6.2.2.1 LOCATION OF THE SITES WITHIN THE REGION

The general location of the sites is shown in Figure 6.5.

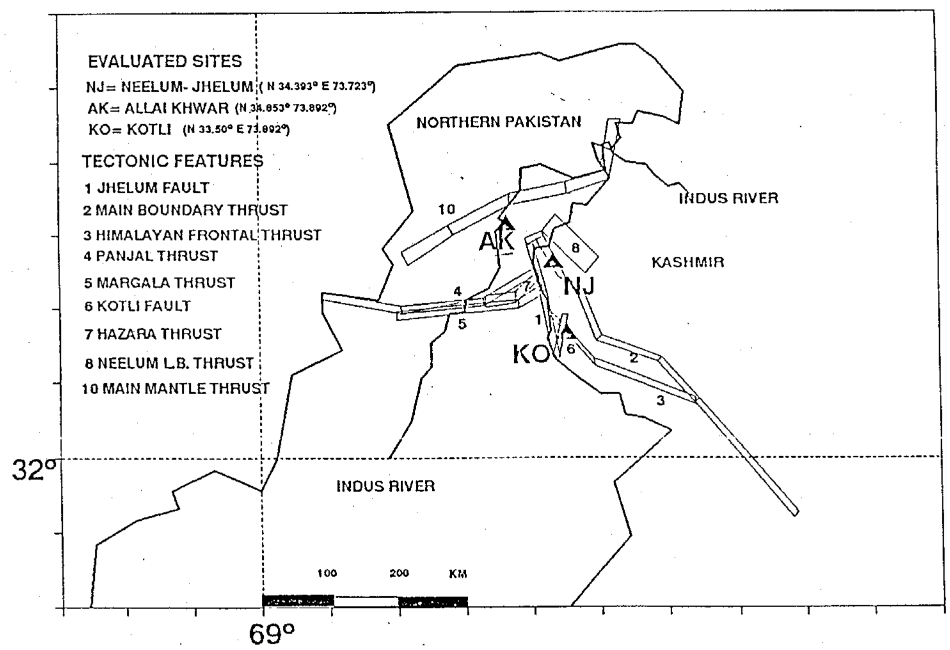

Fig. 6.5: **General location map of Kotli and Allai Khwar**

The Kotli Dam site is located towards the southeast of the Hazara-Kashmir Syntaxis. The dam site itself is located very close to a local fault. Additionally, it is in relative proximity of the Himalayan Frontal Thrust.

The Allai Khwar site is located to the northwest of the syntaxis, near Main Mantle Thrust.

6.2.2.2 GEOLOGIC SETTING

6.2.2.2.1 KOTLI HPP

Physiography
The proposed project is located on the Punch River near Kotli. The Punch River is surrounded by low to moderately high relief mountains with stable slopes. Ridges and valleys of the area generally follow the strike direction of the bedding.

Geology
The project area is located amid the foothills of the western Himalayas of Kashmir which are mainly comprised of the Siwalik and the Rawalpindi group of rocks of Miocene to Pleistocene age. Just upstream of Kotli, the Murree Formation has a faulted contact (Himalayan Frontal Thrust) with the Siwalik formation.

In a limited area (Tatapani Dandli Dhanan) upstream of Kotli, the Murree formation has a faulted contact with Tria-premocarboniferous material. There is also a secondary fault, probably a strike-slip, close to the dam. The fault is briefly described in the next section.
All the components of the proposed project are located on the Siwaliks and the Murree Formation. The Siwaliks are composed of alternate beds of sandstone, shale, and clay stones in varying proportions with dominance of sandstone.

6.2.2.2.2 ALLAI KHWAR HPP

Physiography
The proposed project is located on the Allai Khwar Nullah which is a tributary of the Indus River. It originates from very high relief mountains having a large catchment area. The nullah flows in the EW direction joining the river Indus about 6.5 km downstream of Besham Qila. The nullah has a steep gradient with very steep slopes.

Geology
The Allai Khwar site is located in an area composed of a sequence of metamorphic rocks consisting of gneisses, amphibolites, shales, and calcareous series. Regionally there are three major geotectonic divisions (Khan Tahirkheli and Quasim Jan) i.e. the Indian Mass, the Asian Mass, and the Kohistan Island Arc being divided by the well-known Northern Megashear and the newly deciphered Main Mantle Thrust. The project area is situated on the Indian Mass near MMT and Kohistan sequence.

The rocks of the Indian Mass are dominantly Pellitic rocks called Hazara, Dogra, and Manki slates or Swat-Buner and Besham Group. In the close vicinity of MMT, the frequency of amphebolites, gneisses, and marble shows a marked increase.

South of the Main Mantle Thrust on the Indian Mass, are the Hazara slates. Such slates range in metamorphic grade from slaty shales to phyllitic schists, sandstones to quartzites, and semi to medium crystalline limestones. Thus, the degree of metamorphism in this area is generally low except in the vicinity of the highly deformed areas. Generally there is an increase in metamorphism from the south towards the MMT in north.

6.2.2.3 LANDSLIDE POTENTIAL

The physiography of the area with its steep walled valleys and the complex geology are two factors converging on a large landslide potential. It is common to find the debris of landslides everywhere along the valleys demonstrating the extent of the problem. Landslides can be induced by gravity after erosion has weakened the slopes, by the weather including rain, snow and alternate freezing and thawing of ice. Then there are the earthquake induced landslides and rockslides. Zaruba/Mecl (1969) and Veder (1979) provide additional subdivisions of slides. In any case, one should underline that earthquake induced landslides are the more likely because of severe weathering.

These conditions indicate that when assessing the seismic hazard of sites, not only ground shaking should be considered as is often done. A comprehensive geotechnical investigation should assess the general landslide potential. Knowing the general potential, the seismic landslide potential can be assessed with the aid of the results of evaluations like the one in this report.

6.3 DATA COLLECTION

The seismic hazard analysis includes the identification of the tectonic and geologic features affecting the project areas, analyses of historical and instrumental seismicity and the study of the seismotectonic set-up of the region. The gathering of seismotectonic information for a project area includes the review of basic geology and tectonics within a 200 km radius of each site with particular attention to the mapped faults; review and evaluation of both, historical and instrumental seismicity to understand the seismic pattern of the region.

The main sources of seismic data are the earthquake catalogs of the US National Oceanic and Atmospheric Administration (NOAA). The NOAA database can now be accessed via Internet. It consists of various catalogs covering different regions of the world. Some have a worldwide coverage, other cover specific sectors of the planet. To study an area of the world, a geographic window has to be defined and the applicable catalogs are scanned to select the seismic records that fall within the window.

Following catalogs are available:

- PDE-EQH-USE Catalog - Worldwide Preliminary Determination of Epicenters, US Geological Survey
- Special International Earthquake Catalog, NOAA
- Soviet Earthquake Catalog
- People’s Republic of China
- Multiscoure Global Data File, NOAA

The PDE Catalog contains comprehensive data with worldwide coverage although the main set of data cover since the 1960’s. The international Catalog yields useful information about medium to large sized earthquakes since the beginning of the century to circa 1960. Therefore files No.1 and N0.2 are complementary for the region.

The Soviet Catalog provides numerous records but only in a band around the former Soviet Border. Thus they are not homogenous in space and therefore very seldom be used for other regions in the rest of the world.

The Chinese Catalog does not yield any information useful for the study areas outside china.

The Multisource Global Data file only provides information already contained in the International Catalog.

With help of this information, a more specific window can be created covering the nearby area of the project. An example of the data file obtained from NOAA is given in Table 6.1 and Table 6.2. While Table 6.1 a part of the listing of the NOAA data set, Table 6.2 gives the summary of events as a function of the year and the magnitude. The example covers the area of a circle around the Project Golen Gol site N 35.949 E71.959 with a diameter of the circle of 400 km. The depth ranges from 0 to 50 km. The extreme dates of data set are from 13 April 1907 to 23 November 1995. The number of events in the aforementioned area and time is 647.

Table 6.1: **Extract from seismic data set, Golen Gol, Hindukush**

Data Source: PDE + International NOAA FILE I + 2
Window is circle around Golen Gol Project site N 35.949 E 71.959
Diameter of the circle: 400 Km.
Range of depths: 0 to 50 Km.
Extreme dates of data set: 13-04-1907 23-11-1995
Number of events in the window : 647

SRC	YEAR	MO	DAY	LATIT	LONGIT	DEPTH	ASSESSED MAGNITUDE		geog	ms	mb	
SSR	1907	4	13.398610	36.500	70.500	30.	5.30L1	6	718	5.30MSH	.00	FFFZ
SSR	1926	3	27.483450	36.000	70.000	15.	5.50L1		718	5.50MSH	5.50SSR	DGFZ
SSR	1927	6	24.472450	36.400	70.500	15.	5.20L1		718	5.20MSH	5.10SSR	DGFZ
SSR	1934	11	19.968550	36.600	71.400	15.	4.90L1		717	4.90MSH	5.20SSR	DGFZ
SSR	1936	11	11.716250	37.500	72.200	20.	5.40L1		715	5.40MSH	5.70SSR	DHFZ
SSR	1938	5	24.401000	36.700	73.800	15.	5.00L1		720	5.00MSH	5.40SSR	DGFZ
SSR	1938	8	5.594602	36.800	71.000	15.	5.00L1		717	5.00MSH	5.20SSR	DGFZ
SSR	1939	6	19.929630	37.300	71.400	15.	5.10L1		717	5.10MSH	5.40SSR	DGFZ
SSR	1940	7	17.275230	36.800	71.500	15.	5.70L1		717	5.70MSH	5.70SSR	DGFZ
SSR	1955	7	12.056800	36.500	71.000	15	5.00L1		717	5.00MSH	4.30SSR	BEFZ
SSR	1956	1	23.671190	37.400	72.500	8.	5.80L1	8	715	5.80MSH	.00	BEDZ
SSR	1956	10	13.360030	36.300	71.200	30.	5.10L1		717	5.10MSH	4.80SSR	CFGZ
SSR	1957	4	4.683580	36.100	67.900	15.	5.30L1		718	5.30MSH	5.30SSR	CFGZ
SSR	1959	12	15.449760	36.300	69.800	20.	5.10L1		718	5.10MSH	4.80SSR	CFGZ
SSR	1960	7	17.218460	36.700	70.000	35.	5.30L1		718	5.30MSH	5.40SSR	CIFZ
SSR	1963	1	12.264100	36.600	70.000	48.	5.10L1	5	718	5.10MSH	5.00SSR	CFGZ
PDE	1963	7	10.093050	36.500	71.000	33.	6.52L4		717	.00	.00	
PDE	1964	1	23.638540	36.900	71.200	28.	5.62L4		717	.00	.00	
PDE	1964	7	7.883722	35.800	73.400	19.	5.06L4		720	.00	.00	
PDE	1964	1	29.837530	35.600	73.600	33.	5.96L4		720	.00	.00	
PDE	1966	2	19.696850	37.500	70.500	27.	4.34L4		717	.00	.00	
PDE	1966	5	7.769607	34.600	70.700	19.	5.62L4		709	.00	.00	
PDE	1966	8	24.115960	37.400	73.000	38.	4.16L4		715	.00	.00	25
PDE	1966	10	1.318405	34.700	71.000	36.	4.52L4		710	.00	.00	
PDE	1967	3	4.590349	36.839	71.015	45.	5.06L4		717	.00	.00	10
PDE	1967	3	25.157050	34.650	71.069	43.	3.90L4		710	.00	.00	
SSR	1967	4	24.368854	37.300	72.500	10	5.20L1	7	715	5.20MSH	5.20SSR	ADEZ
PDE	1967	4	24.368900	37.365	72.611	48.	6.10LZ		715	.00	6.10UPP	160
PDE	1968	3	3.390761	34.700	72.300	33.	5.06L4		710	.00	.00	27
PDE	1968	4	9.051998	35.500	73.300	14.	5.42L4		720	.00	.00	10
SSR	1968	9	15.593050	37.150	72.570	30.	5.00L1		715	5.00MSH	.00	ADI
PDE	1968	9	15.593000	37.167	72.737	35.	5.06L4		715	.00	.00	M 16*
SSR	1968	10	30.121770	37.470	73.200	20.	4.90L1		715	4.90MSH	.00	BDE
PDE	1968	11	1.887561	37.579	72.196	41.	4.16L4		715	.00	.00	8*
PDE	1969	1	27.457950	37.298	71.487	49.	5.06L4		717	.00	.00	20
PDE	1969	5	15.860950	34.605	70.899	22.	5.78L4		709	.00	.00	49
PDE	1969	12	29.756200	37.028	71.778	42.	4.16L4		717	.00	.00	
PDE	1970	2	22.787120	37.101	72.031	33.	4.16L4		715	.00	.00	M 9
PDE	1970	4	23.794410	37.444	72.652	46.	4.86L4		715	.00	.00	62
PDE	1970	7	26.854580	34.807	73.225	35.	4.88L4		710	.00	.00	M 12
PDE	1971	12	27.874700	35.830	73.121	10.	5.42L4		720	.00	.00	24
PDE	1972	4	2.148833	36.129	73.618	47.	4.70L4		720	.00	.00	48
PDE	1972	8	15.378540	34.902	71.367	33.	4.16L4		717	.00	.00	M 30*
PDE	1972	9	3.790135	35.979	73.417	36.	4.20L1	4	720	6.20MSKF	.00	
SSR	1972	9	3.700142	36.000	73.560	40.	6.20L1		720	6.20MSH	.00	BDE
PDE	1972	9	27.850640	35.170	73.057	39.	4.70L4		720	.00	.00	70
PDE	1973	1	15.783840	36.064	73.365	33.	2.54L4		720	.00	.00	8*
PDE	1973	4	14.865390	36.110	73.494	33.	3.09L4		720	.00	.00	M 9*
SSR	1973	10	12.120900	37.700	71.880	5.	5.20L1	7	717	5.20MSH	.00	BDEZ
PDE	1975	12	9.108158	35.881	73.261	33.	4.70L4		720	.00	.00	
PDE	1975	12	17.421870	36.300	70.844	53.	5.98L4		718	.00	.00	
PDE	1976	5	11.991500	35.652	72.107	58.	4.16L4		710	.00	.00	
PDE	1976	7	5.304055	37.411	72.483	33.	4.90L1		715	4.90MSH	.00	
PDE	1976	12	18.143180	37.346	72.917	48.	5.44L4		715	.00	.00	11
PDE	1974	12	28.508140	35.054	72.870	22.	6.20L1		710	6.20MSHC	6.10UPK	113
PDE	1974	12	30.643890	36.709	71.603	40.	4.42L4		717	.00	.00	16
PDE	1975	1	20.334430	35.388	73.435	33	4.54L4		720	.00	.00	
PDE	1975	4	7.279608	34.939	73.090	37.	4.70L4		710	.00	.00	
PDE	1975	5	10.565760	35.132	72.922	33.	3.80L4		710	.00	.00	

Table 6.2: **Seismic Recurrence (Radius = 200 km; Depth < 50 km), Golen Gol, Hindukush**

	DISTRIBUTION OF MAGNITUDES															
Year	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	Total
1907	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
1926	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
1927	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
1934	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
1936	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
1938	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2
1939	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
1940	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
1953	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
1954	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
1956	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
1957	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
1959	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
1960	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
1963	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	2
1964	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	2
1965	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
1966	0	0	0	0	0	1	2	1	0	0	0	0	0	0	0	4
1967	0	0	0	1	0	0	0	0	2	0	1	0	0	0	0	4
1968	0	0	0	0	0	1	1	1	3	0	0	0	0	0	0	6
1969	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	3
1970	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	3
1971	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
1972	0	0	0	0	0	0	1	2	0	0	2	0	0	0	0	5
1973	0	0	0	1	1	1	0	1	1	0	0	0	0	0	0	5
1974	0	0	0	0	1	0	1	2	0	0	1	0	0	0	0	5
1975	0	0	0	2	0	1	1	1	0	0	0	0	0	0	0	5
1976	0	0	1	0	2	1	1	0	0	0	0	0	0	0	0	5
1977	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	3
1978	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	2
1979	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	3
1980	0	0	0	1	0	2	2	0	0	0	0	0	0	0	0	5
1981	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	2
1982	0	0	0	1	0	4	3	1	0	0	0	0	0	0	0	9
1983	0	0	0	0	5	8	4	2	0	0	0	0	0	0	0	19
1984	0	0	0	0	1	7	10	1	1	1	0	0	0	0	0	21
1985	0	0	0	1	10	20	12	0	0	0	0	0	0	0	0	43
1986	0	0	0	2	7	9	5	4	1	0	0	0	0	0	0	28
1987	0	0	0	0	2	8	3	0	0	0	0	0	0	0	0	13
1988	0	0	0	0	12	18	9	0	2	0	0	0	0	0	0	41
1989	0	0	1	4	3	8	4	2	0	0	0	0	0	0	0	22
1990	0	0	1	4	13	9	8	4	2	0	2	0	0	0	0	43
1991	1	0	3	15	19	27	16	12	3	0	0	0	2	0	0	98
1992	0	1	6	18	18	30	14	9	0	2	0	0	0	0	0	98
1993	0	0	1	4	19	26	8	8	4	0	2	0	1	0	0	73
1994	0	0	0	6	8	13	18	5	1	1	2	0	0	0	0	54
1995	0	0	0	2	1	1	0	0	0	0	0	0	0	0	0	4
TOTALS	1	1	14	62	123	197	127	64	36	9	10	0	3	0	0	647

Additionally to the analysis and evaluation based on available data banks, specific field studies should also be carried out. It is necessary that detailed seismotectonic studies are carried out for a better understanding of the potential seismic sources governing the expected ground motion of a project area.

Especially in regions with a generally high seismic activity, also active earthquake sources need to be identified in the field. The instrumental assessment of seismic activity by means of local networks of seismographs should be undertaken, where planned high head hydropower developments might be effected by. For this purpose the possibility of establishing a seismographic network should be evaluated.

Moreover accelerographs should be installed. These instruments yield complementary information that seismographic networks cannot gather. These instruments are strategically distributed to record detailed information about the strong ground motion during an intense earthquake. They are stand-by instruments that only get activated operation like the seismographs. It is recommended to consider the expansion of a seismic network in project areas with the inclusion of a sufficient number of accelerographs.

6.4 DATA PROCESSING

6.4.1 POTENTIAL SEISMIC SOURCES

To evaluate the worst possible earthquake intensities at the sites of interest the following faults were taken into consideration:

Source No.	*Name*
1	Jhelum fault
2.	Main Boundary Thrust (MBT)
3.	Himalayan Frontal Thrust (HFT)
4.	Panjal Thrust (PT)
5.	Margala Thrust (MT)
6.	Kotli Fault (KF)
7.	Hazara Thrust (HT)
8.	Neelum Luat Barian Thrust (NLBT)
9.	Trace of a small fault (not included)
10.	Main Mantle Thrust (MMT)

6.4.2 ANALYSIS OF INDIVIDUAL SOURCES

For each of the faults and thrusts listed above, the opinion of geologists was taken into consideration to pinpoint the segments of faults and thrusts appearing to have a higher degree of activity. Much of the information in this respect is even speculative, based on geological judgment. For lack of local seismic networks there is no microseismic evidence that could be used for the purpose of identifying active faulting

The faults of interest are shown in Figures 6.6 to 6.14 which are the worksheets used for the analysis. Assumptions and comments are recorded there. The rationale behind the assumptions is described below in this section.

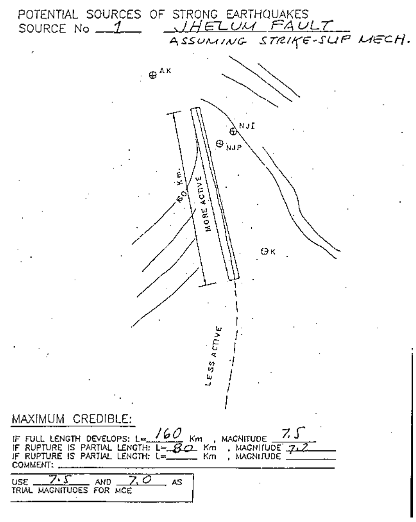

Fig. 6.6: **MCE Analysis – Jhelum Fault**

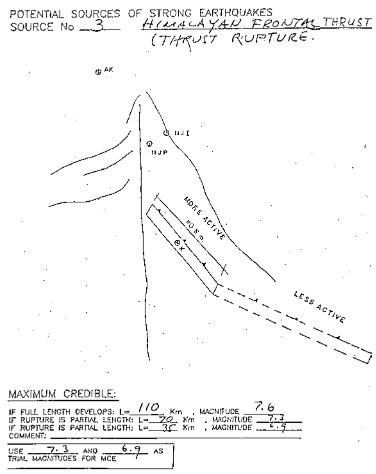

Fig. 6.7: MCE Analysis – Himalayan Frontal Thrust

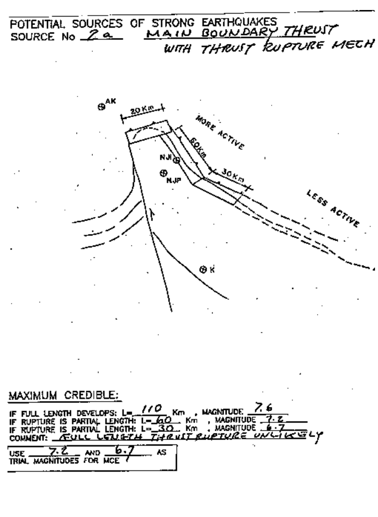

Fig. 6.8: MCE Analysis – Main Boundary Thrust

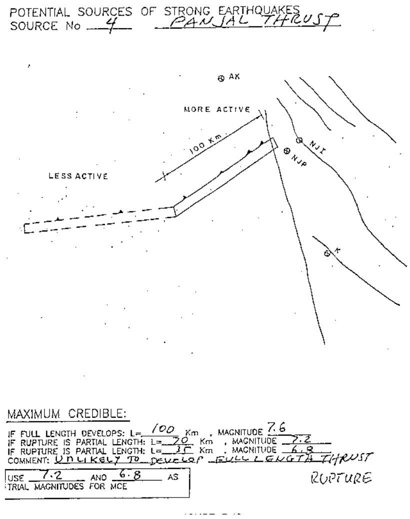

Fig. 6.9:MCE Analysis – Panjal Thrust

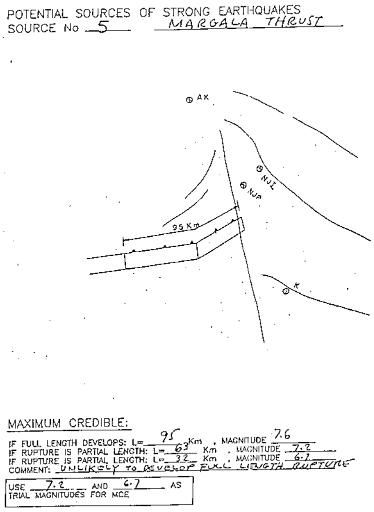

Fig. 6.10: MCE Analysis – Margala Thrust

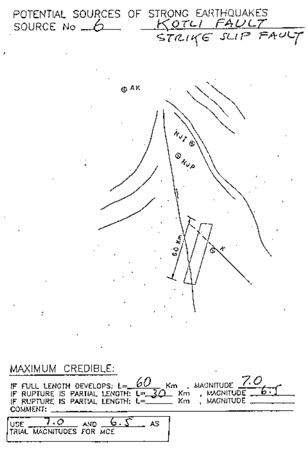

Fig. 6.11: MCE Analysis – Kotli Fault

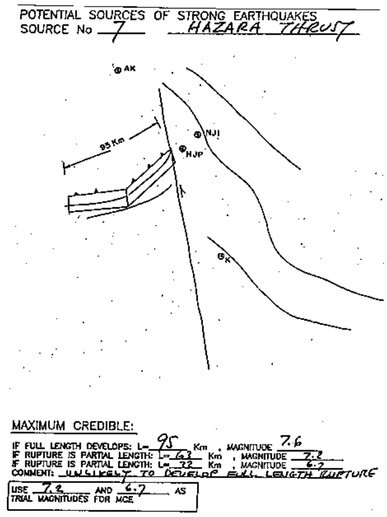

Fig. 6.12: MCE Analysis – Hazara Thrust

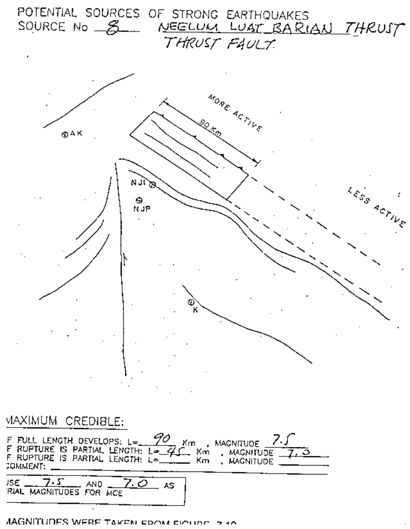

Fig. 6.13: MCE Analysis – Neelum Luat Barian Thrust

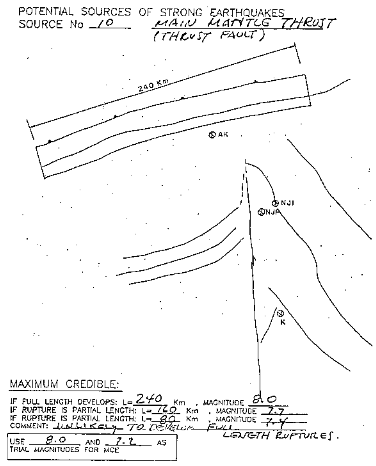

Fig. 6.14: MCE Analysis – Main Mantle Thrust

6.4.2.1 MAXIMUM RUPTURE LENGTH

To assess the maximum credible event two possibilities were considered:

- The maximum earthquake corresponds to a fault rupturing its full length.
- The maximum earthquake corresponds to a fault rupturing half its length.

6.4.2.2 MAGNITUDE ASSUMPTION

To assign the magnitude that would correspond to the assumed maximum rupture, a set of magnitude-rupture empirical relationships was used. The relationships are shown in Figure 6.15. Because of the difficulty to assess rupture lengths for thrust fault-ruptures as a class, general relationships were used. Below magnitude 6.5, an average between the Housner and Jennings, 1982 curve and the Oases, 1978 curve originally developed for Alaskan subduction earthquakes was used. For larger magnitude earthquakes the Oases relationship appears to be biased in the upper ranges, probably by data of long strike-slip ruptures; thus, some Mexican subduction data were plotted and a curve fitted; this yields a range of possibilities in the upper magnitude reaches. The reason for resorting to the subduction data is that one may expect more parallelism between major thrust ruptures and subduction than between thrust and strike slip faulting. In any case, values for the ruptures of the specific region were drawn from the middle of the field between curves in Figure 6.15. The magnitude values resulting from these assumptions were deemed reasonable.

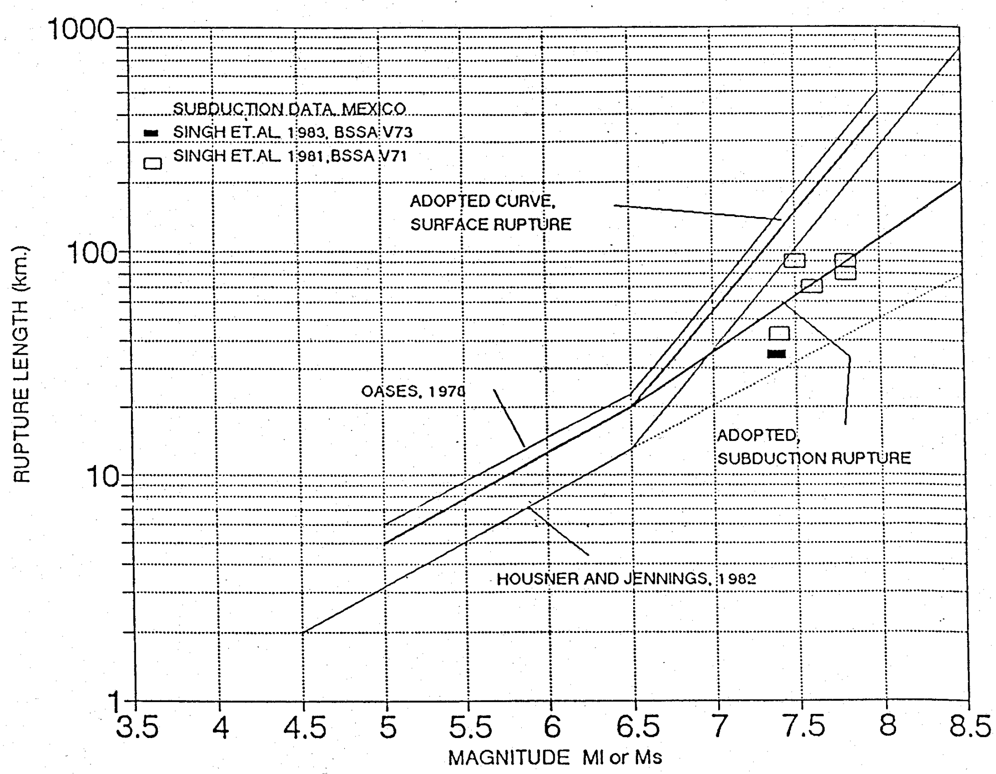

Fig. 6.15: **Earthquake magnitude vs. rupture length**

From the rupture length assumptions and the rupture-magnitude assumptions two magnitudes were inferred. In other words, the maximum credible magnitude for each source was assessed as a bracket, underscoring the uncertainty associated with the value of this parameter.

6.4.3 SEISMIC INTENSITY PARAMETERS

6.4.3.1 PGA, PGV, PSRV AND PSA SPECTRUM

The earthquake intensity parameters used for this kind of hazard assessment are peak ground acceleration (PGA), peak ground velocity (PGV), and Pseudo-relative velocity spectral ordinates (PSRV) and are calculated using attenuation relationships by Joyner and Boore, 1988.

A fourth parameter of importance is the pseudo-acceleration response spectrum (PSA). The ordinates of this spectrum are derived from the ordinates of the PSRV by multiplying them by 2xPIxFreq (Hz); if the velocity is in cm/sec the results is in gals, i.e. cm/sec^2. The PSA is of great importance for structural analysis.

6.4.3.2 ATTENUATION RELATIONSHIP

Dozens of attenuation relationships have been derived in the past decades. The attenuation relationships usable in hazard assessments are statistically based. A general discussion on attenuation relationships can be found in Campbell, 1986. For the resent evaluation the attenuation relationships by Joyner and Boore, 1988, were used. Examples of the format of the J&B attenuations is given in Table 6.3.

Table 6.3: **Spectra Attenuation Relationships (Joyner and Boore, 1988)**

T [sec]	a	b	c	d	h	k	s	sigma
	Pseudo-velocity [cm/sec] 5% damping							
0.10	2.16	0.25	-0.06	-1.0	11.3	-0.0073	-0.02	0.28
0.15	2.4	0.3	-0.08	-1.0	10.8	-0.0067	-0.02	0.28
0.20	2.46	0.35	-0.09	-1.0	9.6	-0.0063	-0.01	0.28
0.30	2.47	0.42	-0.11	-1.0	6.9	-0.0058	-0.04	0.28
0.40	2.44	0.47	-0.13	-1.0	5.7	-0.0054	-0.10	0.31
0.50	2.41	0.52	-0.14	-1.0	5.1	-0.0051	-0.14	0.33
0.75	2.34	0.60	-0.16	-1.0	4.8	-0.0045	-0.23	0.33
1.00	2.28	0.67	-0.17	-1.0	4.7	-0.0039	-0.27	0.33
1.50	2.19	0.74	-0.19	-1.0	4.7	-0.0026	-0.31	0.33
2.00	1.12	0.79	-0.20	-1.0	4.7	-0.0015	-0.32	0.33
3.00	2.02	0.85	-0.22	-0.98	4.7	-0.0	-0.32	0.33
4.00	1.96	0.88	-0.24	-0.95	4.7	-0.0	-0.29	0.33
	Peak acceleration [g]							
	0.43	0.23	0.00	-1.00	8.00	-0.0027	0.00	0.28
	Peak velocity [cm/sec]							
	2.09	0.49	0.00	-1.00	4.00	-0.0026	0.17	0.33

$$\log y = a + b(M-6) + c(M-6)2 + d\log R + kR + s \pm \varepsilon$$

with:
y – randomly oriented horizontal component
s<>0 soil site ≧ 5m thickness; s=0 rock site
5 ≦ M ≦ 7.7; M moment magnitude R = (r2 + h2) 0.5
r - distance to the vertical projection on the earth's surface of the nearest point of rupture

6.4.3.3 HORIZONTAL DISTANCE (RO)

To calculate the intensity parameters it is necessary to select the horizontal distance from the rapture plane to the site. This distance is assessed from the map. The mapped surface trace of faults might be taken, although this may not be strictly correct for plane dipping at an angle. If no other data are available, this approach can be considered as accurate enough.

6.4.3.4 FOCAL DEPTH (H)

With regard to the depth of the earthquake, the Joyner and Boore relationships incorporate a fixed depth parameter. Since the depth value is for shallow earthquakes, it is applicable for the maximum credible earthquake assumptions which call for an earthquake as shallow as possible.
The calculation is performed using local depths of 7.5 and 15 km, for acceleration and velocity respectively. As expected, for sites close to the faults and thrusts the focal depth is crucial. The 15 km depth can reduce the maximum intensities by a factor of two.

6.4.3.5 MAXIMUM CREDIBLE SEISMIC INTENSITIES

Figure s 6.6 to 6.14 contain the trial maximum credible intensities and comments. Tables 6.4 and 6.5 summarize the conclusions. Figures 6.16 and 6.17 contain the resulting Pseudo Relative Velocity Spectra. Figures 6.18 and 6.19 contain the resulting Pseudo Acceleration Spectra. Observe that the spectra as well as the other parameters are given as ranges, not as point assessments.

Table 6.4: **MCE Analysis, PGA and PGV Intensity Parameters, Kotli**

Source		Maximum Credible Earthquake Magnitude		R_0 Horiz. Distance [km]	H Depth [km]	Parameters			
						PGA [g]		PGV [cm/s]	
No.	Name	Low	High			Low	High	Low	High
6	Kotli Fault	6.5	7.0	3	8/4	0.39	0.51	42	74
3	Himalayan Frontal Thrust	6.9	7.3	2	8/4	0.50	0.62	74	116
1	Jhelum Fault	7	7.5	20	8/4	0.19	0.24	16	29

Table 6.5: **MCE Analysis, PGA and PGV Intensity Parameters, Allai Khwar**

Source		Maximum Credible Earthquake Magnitude		R_0 Horiz. Distance [km]	H Depth [km]	Parameters			
						PGA [g]		PGV [cm/s]	
No.	Name	Low	High			Low	High	Low	High
10	Main Mantle Thrust	7.2	7.7	15-30	8/4	0.27	0.48	28	73
8	Neelum Luat Barian Thrust	7.0	8/4	60	8/4	0.05	0.07	4	8
2	Main Boundary Thrust - Thrust Comp. - Strike Slip Comp.	 6.7 6.9	 7.2 7.3	 60 60	8/4	 0.04 0.05	 0.06 0.06	 3 4	 6 6
1	Jhelum Fault	7.2	8/4	50	8/4	0.07	0.09	7	10
4	Panjal Thrust	6.8	7.2	70	8/4	0.04	0.05	3	4

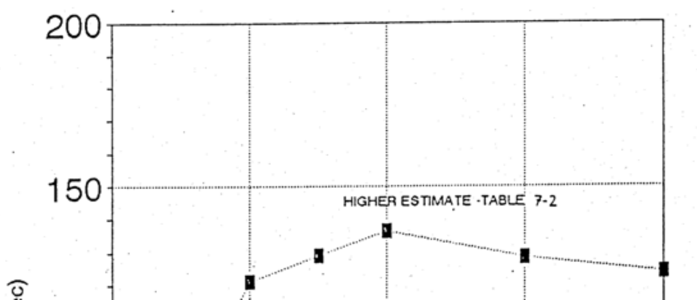

Fig. 6.16: Maximum credible pseudo relative velocity spectra, Kotli

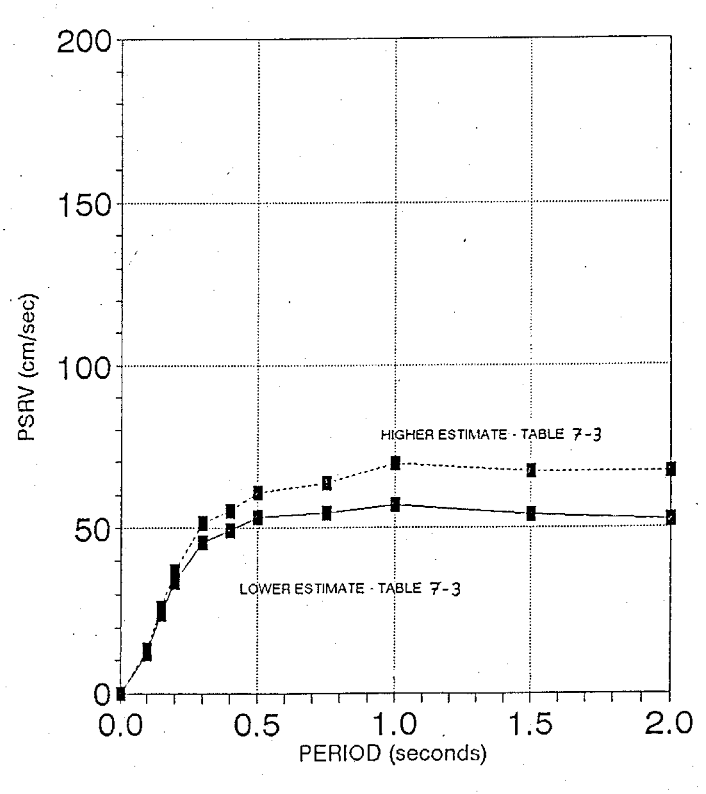

Fig. 6.17: Maximum credible pseudo relative velocity spectra, Allai Khwar

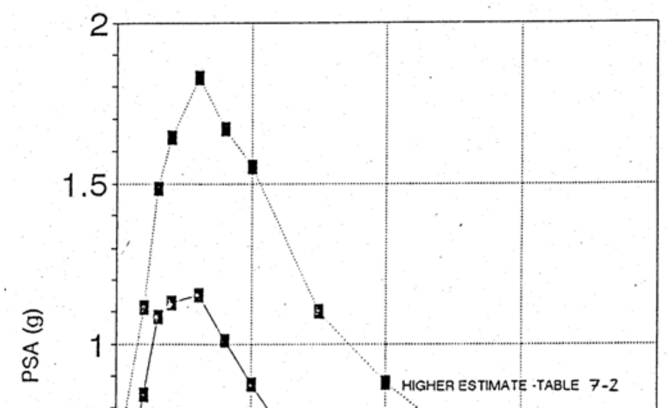

Fig. 6.18: **Maximum credible pseudo acceleration spectra, Kotli**

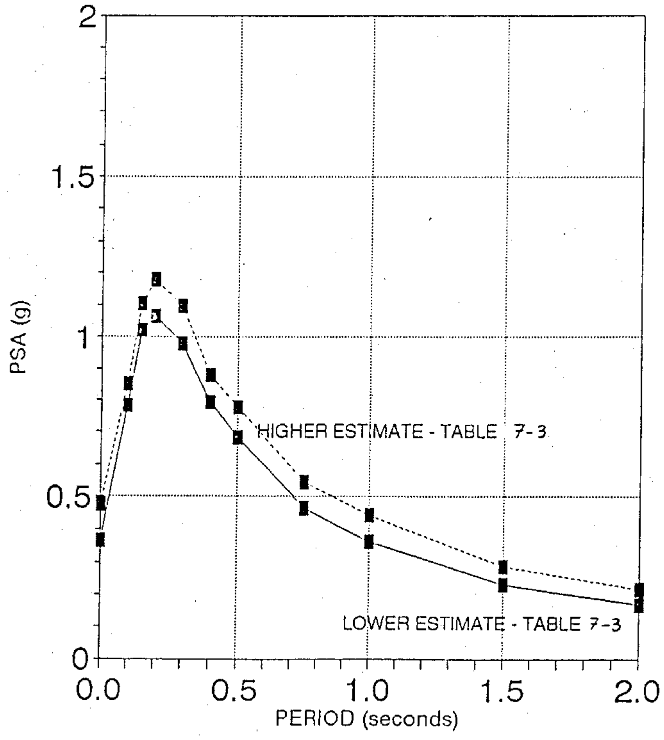

Fig. 6.19: **Maximum credible pseudo acceleration spectra, Allai Khwar**

6.5 SEISMIC HAZARD EVALUATION - DESIGN EARTHQUAKE AT SEVERAL HAZARD LEVELS

The assessment of design earthquakes at various hazard levels requires the estimating of the recurrence of seismic intensities at the sites of interest. The recurrence of seismic intensities is inferred using the method originally devised by Cornell in 1968. It requires data on the location and magnitude of seismicity (i.e. an earthquake catalog); from these data the recurrence of earthquake magnitudes is inferred. The intensities that each magnitude can cause at the sites of interest is calculated knowing the distance between source and target and having a suitable attenuation relationship. The results reported here were numerically evaluated with the program EQRISK (MacGuire, 1977) using the assumptions and performing the tasks described below.

6.5.1 CONVERSION OF MAGNITUDES

Seismic catalogs record particular definitions of earthquake magnitudes. Surface wave magnitude, Ms, is generally considered a good representative measurement of earthquake magnitude in the range 5.5 < M < 7.5, particularly for shallow earthquakes. When surface wave magnitude Ms recordings were not available, magnitudes were converted into Ms scale. Frequently found readings of magnitude in the catalogs scanned are mb (body wave magnitude), Ms (surface wave magnitudes) calculated by the U.S.Geological Survey, and Ms calculated by another authority, for instance a European, Soviet or Chinese seismological agency. Sometimes there are Ms assessments from Cal Tech of Pasadena, California. This diversity of measurements needs to be converted into a single one.

Magnitudes were converted to a common basis using the following conversion rules:

- if Ms (USGS definition) is given, adopt it as magnitude M.
- else, if an alternate Ms value is available, adopt it as M.
- if only mb readings are available convert them to Ms using the method by Wyss and Habermann, 1982:

If year of event < 1963 then

Adopted $$Ms = 1.8 \times mb - 5.2 \quad \textbf{(6.3)}$$

Otherwise $$Ms = 1.8 \times mb - 4.3 \quad \textbf{(6.4)}$$

Unknown Magnitudes

Many records in the catalogs, especially older ones, do include geographical position but do not include a magnitude assessment. This is because the sensitivity of the seismic networks used to detect the events was not good enough to pinpoint certain magnitudes somewhat under the threshold of the network. Such thresholds are not specifically reported by the catalog compilers; the increase in sensitivity with the years has to be guessed at.

In the seismic analysis of Ghazi Gariala, Ambrasseys assigns "lower bound" magnitudes to events with no record of magnitude. He used the following relationship attributed to Middle East events:

$$Ms = 7.14 - 0.04253 \times \left(Year - 1900\right) \quad \textbf{(6.5)}$$

For this project, frequency distributions by magnitude and by year were made for the full data window centered on Pakistan. The window is about 4 million square kilometers and is thus large enough for the intended statistics. For increasingly smaller magnitudes, their years of first reading were plotted against the magnitudes to investigate the magnitude-detecting capability of the PDE and the International catalogs. A linear regression was fitted over the data points. The graphs are shown in Figure 6.6. The resulting statistic for the Pakistan-centered region is

$$Ms = 7.15 - 0.0446 \times \left(Year - 1900\right) \quad \textbf{(6.6)}$$

Year < 1963

Hence, earthquake events for which no magnitude value was available were assigned a lower bound magnitude using the above expression in which "Year" is the year of occurrence of the event.

6.5.2 MAGNITUDE-RECURRENCE RELATIONSHIPS

A recurrence relationship describes the frequency distribution of magnitudes for a seismic source. A simple form of recurrence relationship which is used in most engineering applications is log-linear:

$$Log N(M,t) = a(t) - b \times M \qquad \textbf{(6.7)}$$

where N(M,t) is the number of earthquakes of magnitude "M" or greater expected on the average to occur within a time-period "t". The coefficients "a(t)" and "b" are derived from the statistical analysis of an earthquake data set specifically assembled for the seismic source of interest. The value of a(t) depends upon the source seismic activity and the time period "t" considered. When the period "t" is 1 year, the recurrence is said to be time-normalized and the inverse of N(M,1) is the return period of events of magnitude M or larger. The time-normalized variable is denoted as N'(M).

Area sources

In many regions it is not possible to reasonably assign seismic events to specific seismogenic sources. This was the case for the Northern Pakistan area. In such cases a standard technique to overcome the modeling limitations is to define as the seismic source an area centered at the analyzed site. A seismic data set for the adopted circle is assembled and all earthquakes located within the circle are counted, classified by magnitude and a recurrence relationship is obtained. When performing the seismic hazard analysis, earthquakes are supposed to randomly occur at any place within the defined circle, while their magnitudes are assumed to follow the magnitude-recurrence distribution.

For the sites of interest, circles 200 Km in radius were defined around each site. The PDE Catalog and the International Catalog were scanned out. A separate data set was assembled for each analyzed site including Kotli, Allai Khwar and the Neelum- Jhelum Intake. The general seismic environment and the assumed influence regions are shown in Figure s 6.20 to 6.21. Since two catalogs were used, both had to be merged and then checked for removal of double events.

Aftershocks of major events need to be removed from the data base to prevent bias in the count of number of events and magnitudes, especially if there are main events and numerous trailing smaller events that are only secondary shocks.

However, the data base shows numerous instances of multiple events, in which it is difficult to single out a "main event" because they are series of earthquakes of nearly the same magnitude. Multiple events were not removed and they were counted as separated events in the recurrence statistics.

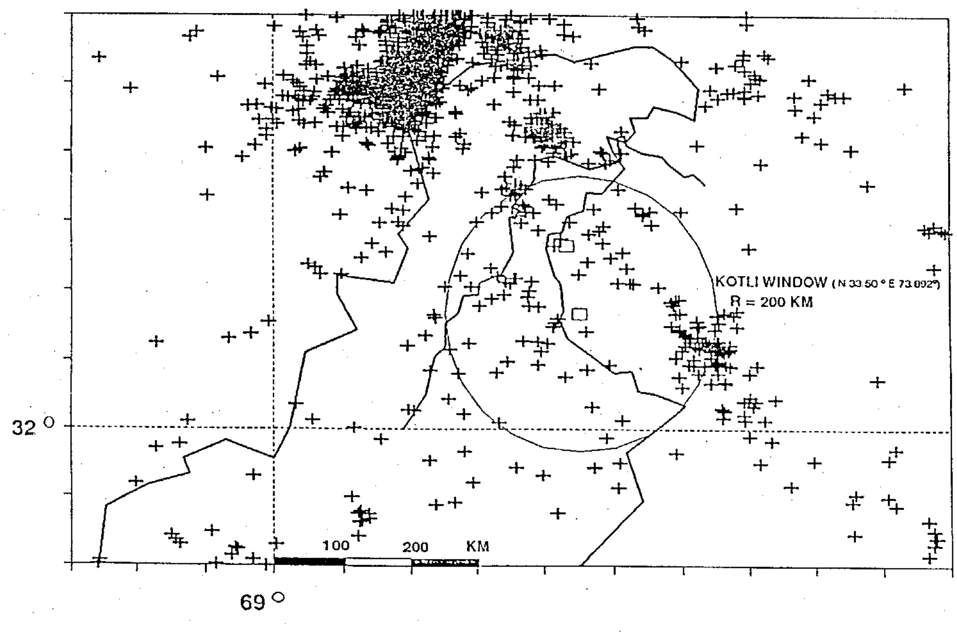

Fig. 6.20: **Data set for seismic recurrence, Kotli**

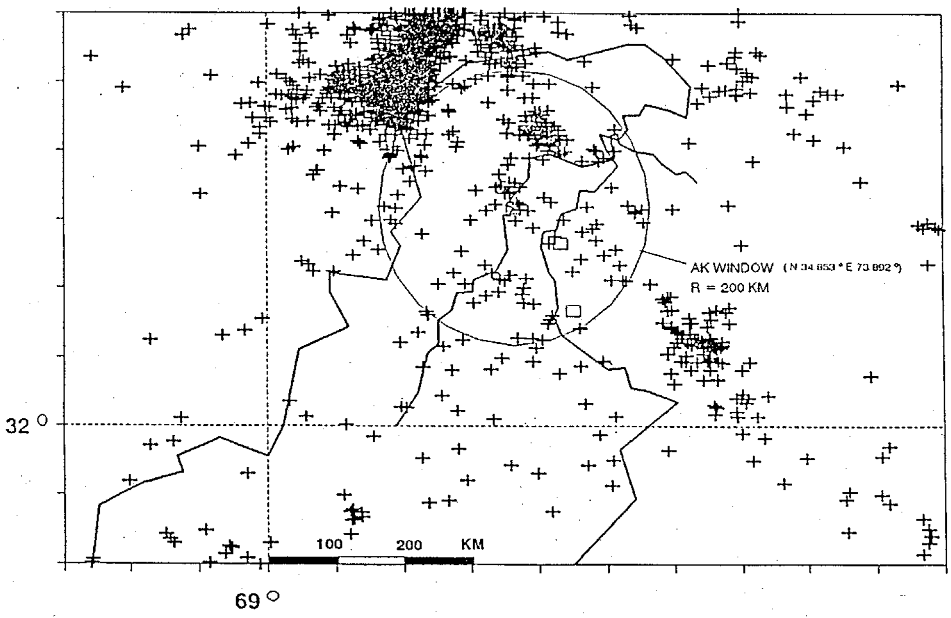

Fig. 6.21: **Data set for seismic recurrence, Allai Khwar**

Pairs of shocks were also found. In these cases the shocks are geographically separated more than the rupture length corresponding to their magnitudes. Pairs when identified were not removed and were counted as separated events for the recurrence statistics.

Similarly foreshocks were not removed from the statistics. Foreshocks are defined as smaller magnitude events close in space and preceding a larger event.

The data base assembled and filtered as described above was then "magnitude converted". All magnitudes were "transformed" into equivalent Ms magnitudes.
Earthquakes of unknown magnitude were assigned lower bound estimates of magnitude.
Deeper events were removed from the statistical recurrence count for each site. According to the literature there is likely to exist a "decollement" or "shaving-off" of the crust at depths of 30 to 40 Km. Sometimes even less. From the surface expressions of the thrusts seismicity dips at a very low angle, nearly horizontal. In order not to exclude this decollement seismicity a depth of 50 Km was selected to separate deeper from shallower events. Only events less than 50 Km in depth were considered for the recurrence statistics. This approach is deemed conservative and could even be relaxed in future seismic hazard assessments.

The earthquake data set for each site was classified into 0.5 magnitude intervals and the absolute counting of events was performed. However such counts are time-biased because the data set was drawn from catalogs whose magnitude detection capabilities have been improving with time. Therefore the absolute count of each magnitude was divided by an appropriate time span. The appropriate time span was obtained as follows:

$$Yr = 1900 + (7.15 - Ms)/0.0446 \quad \textbf{(6.8)}$$

Yr is the statistical assessment of the year in which magnitude Ms started to be detected. The time span of the available is:

$$T = 1990 - Yr \qquad \textbf{(6.9)}$$

where 1990 or another year is the date of the last event in the data base.

Based on the time normalized count N'= N/T a regression was run on the data obtaining magnitude-recurrence relationships shown in Figure s 6.22 and 6.23 for the sites of interest. The corresponding best fit equations are:

Kotli $$Log(N) = 2.92 - 0.683Ms \qquad \textbf{(6.10)}$$

Allai Khwar $$Log(N) = 4.02 - 0.884Ms \qquad \textbf{(6.11)}$$

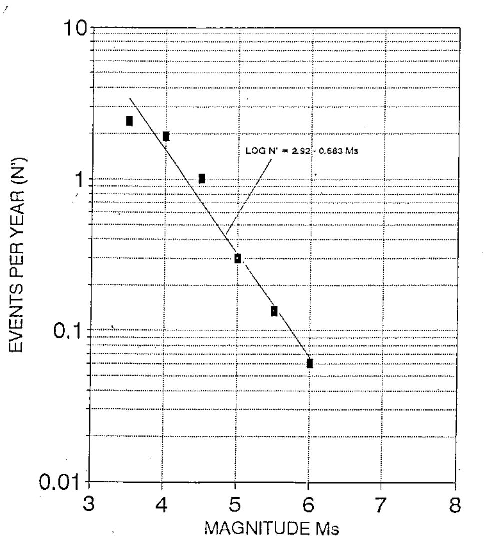

Fig. 6.22: Seismic Recurrence, Kotli

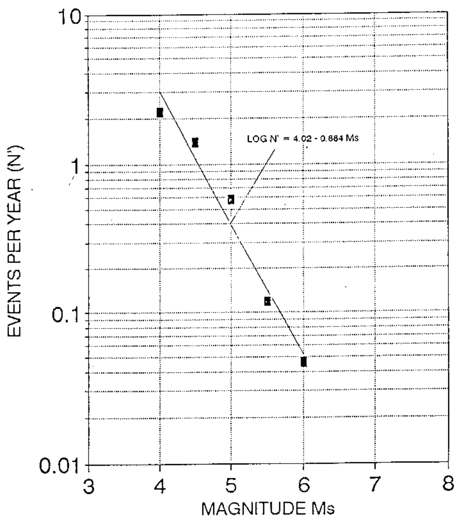

Fig. 6.23: **Seismic Recurrence, Allai Khwar**

6.5.3 EVALUATION OF INTENSITY PARAMETERS

For the determination of intensity parameters at various hazard levels a straightforward tool was selected: the program EQRISK (McGuire, 1977 / PC version 1985). This program is very easy to operate and runs in PC personal computers without large demands of capacity. Its limitations, which to some extent reside in the seismic source geometrical model (e.g. it only accepts constant depth sources) were not severe in the Pakistan assessment because of the simplicity of the analytical model of the seismic environment that was used in the current evaluation.

The program EQRISK has many advantages. It has interchangeable formats for attenuation laws; the computer code is relatively transparent and can be easily modified. It has a good User's Guide. The advantages outnumber the shortcomings. As WAPDA engineers become proficient in hazard analysis, other computer codes can be installed in Lahore.

No attenuation law has been developed in Pakistan or in the south Asian region because of unavailability of strong motion data. For the present evaluation, the Joyner and Boore (1988) attenuation was selected as already mentioned in previous sections. The attenuation relationship format and coefficients are given in Table 6.3. The Joyner and Boore attenuation is nominally devised for a Magnitude, Mo, scale. In this assessment all magnitudes were converted to Ms magnitudes. However, the Ms magnitudes did not exceed 7.0. Hence, no further conversion is needed since Mo is supposed to match Ms for magnitudes below 7.5.

6.5.4 PSA AND PSRV - DESIGN SPECTRA

All of seismic design parameters that can be evaluated on basis of the Joyner and Boore attenuation relationship were computed using seismic recurrences described below. Based on the results of the maximum credible events, two runs of EQRISK were made for each, the lower and the higher estimates of maximum magnitude.

Since there was no direct assignment of seismicity to specific seismic sources, the entire circle defined around each site was used as a constant depth seismic source. The depth assigned in each case corresponds to the depths prescribed in the Joyner and Boore attenuation formula. In case of Allai Khwar this rule was modified since the main seismic source, the MMT, is about 30 km away. Hence the lower estimate run was made with the closest distance of 30 km and the higher estimate with a closest estimate of 15 km.

For each site, several runs of EQRISK were made: for PGA, PGV and for relative velocity spectral ordinates at various frequencies. The corresponding acceleration spectral ordinates were derived from velocity ordinates using the appropriate conversions. Each of the 8 parameters were evaluated at 200, 500 1000 and 2000 year return periods. In fact, the computations were actually carried out for longer return periods but these already begin to overlap with the maximum credible events. In these cases it is preferable to rely on the more straightforward concept of MCE. Hence, only the first four hazard levels were incorporated into the results and these were bounded with the MCE results.

6.5.4.1 SEISMIC HAZARD GRAPHS

The decision of when to use PGA and when PGV is a choice of the structural and earthquake engineers that use the design parameters. Since the technique of reading either graph is the same, only the PGA graph will be described.

Peak Ground Acceleration Seismic Hazard Graphs

Results are given in Figures 6.24 and 6.25. The graphs are read selecting a hazard level on the abscissas and reading the corresponding PGA on the ordinates. The hazard level can be selected in either of three ways:

a) by return period at the bottom of the graph
b) by annual probability at the top of the graph
c) choosing one of the letter keys displayed along the abscissas

For example, according to Figure 6-24, an ordinary building at Kotli can be designed on basis of a 100-gal PGA. This is because ordinary buildings can be designed against a hazard level A (200 year return period). The same building can be designed on the basis of an 80-gal PGA at Allai Khwar.

As another example, a diversion dam or a barrage whose failure would have only economic consequences could be designed for a return period of about 1000 years (hazard level C in the graph), meaning a PGA of about 130 gals in Allai Khwar and 170 gals in Kotli.

On the other hand, a very important facility whose failure could imperil the lives of thousands of persons, should be designed at least at a 400-gal PGA level in Kotli and 250 gal at Allai Khwar (hazard level E in the graph). This variation of loading from site to site at a fixed hazard level is the basis of a "uniform risk" structural design. However, for very important facilities, the MCE assessment should be taken into consideration.

The hazard graphs are also useful when seismic designs are required at two or three seismic loading conditions. Very important facilities are structurally verified not to collapse if the maximum credible earthquake were to occur, although severe damage is acceptable under this condition. Additionally, for these important structures an Operating basis Earthquake (OBE) is defined, at which only minor damage is acceptable. The structures of the project and their contents and equipment should remain functional. Any damage should be easily repairable after the occurrence of an earthquake with ground motion not exceeding the OBE design parameters. The acceptable risk of having the facility out of operation is decided by the agency managing the facility.

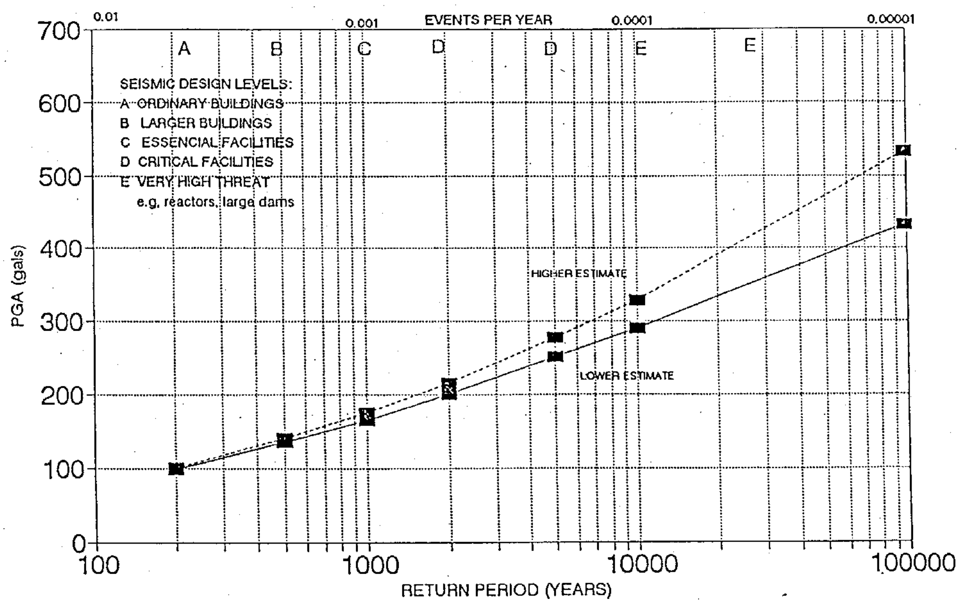

Fig. 6.24: Peak ground acceleration, Kotli

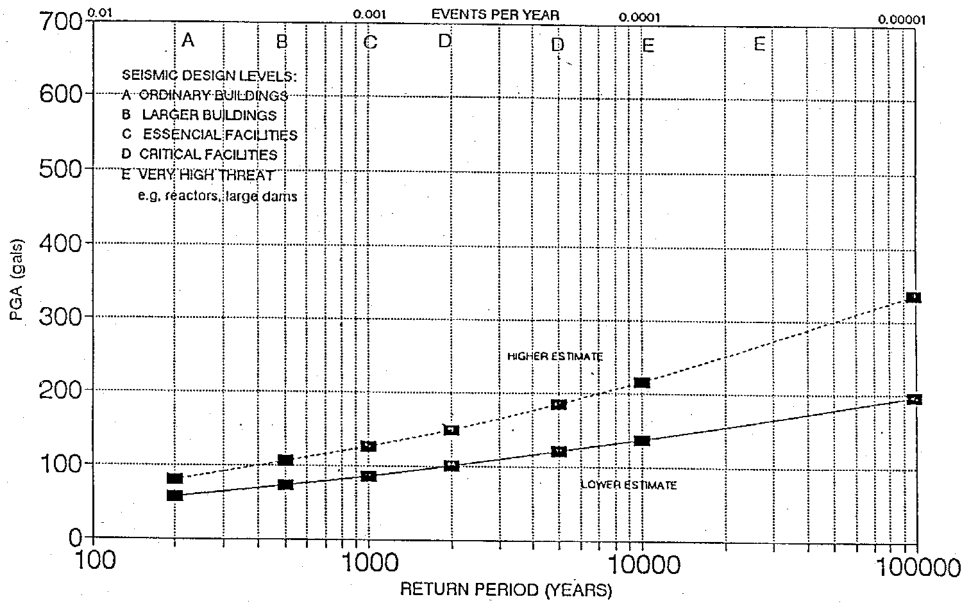

Fig. 6.25: Peak ground acceleration, Allai Khwar

Peak Ground Velocity Seismic Hazard Graphs
These have the same pattern as PGA graphs. Average values are given in Figure 6.26.

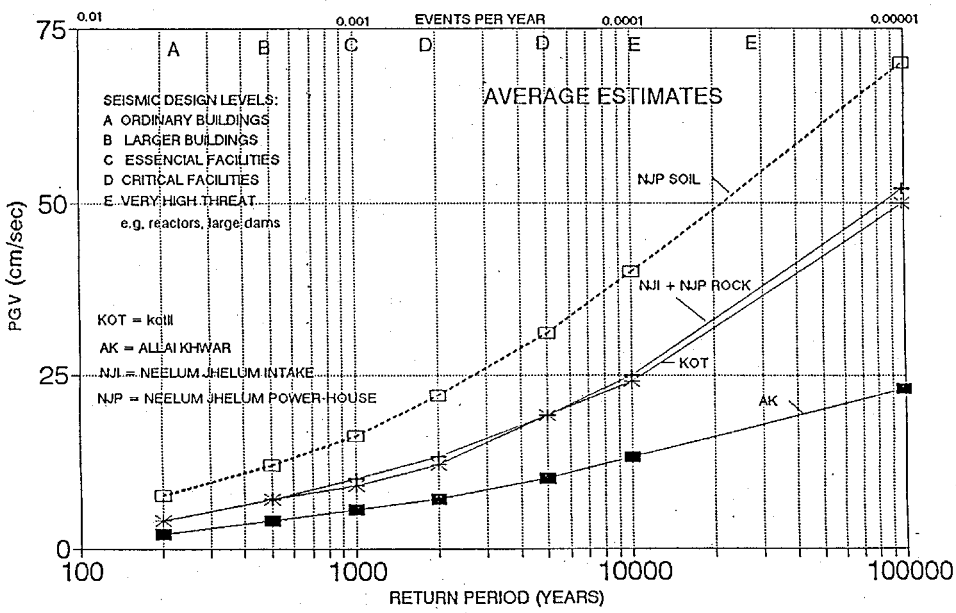

Fig. 6.26: **Peak ground velocity – average estimates**

6.5.4.2 PSA AND PSRV - DESIGN SPECTRA

Several pseudo-relative velocity spectral ordinates were calculated for each site at the hazard levels mentioned at the beginning of Section 6.5 (0.005, 0.002, 0.001, 0.0005 annual probabilities). Results are given for Allai Khwar, Kotli, the Neelum-Jhelum Intake and separately, for the powerhouse site. Additionally, at this latter site two sets of spectra were calculated, one for rock conditions and the other for soil conditions. Figures 6.27 and 6.28 contain the resulting sets of spectra. Each set of spectra is complemented with its corresponding tentative maximum credible earthquake as illustrated in Figures 6.16 to 6.19.

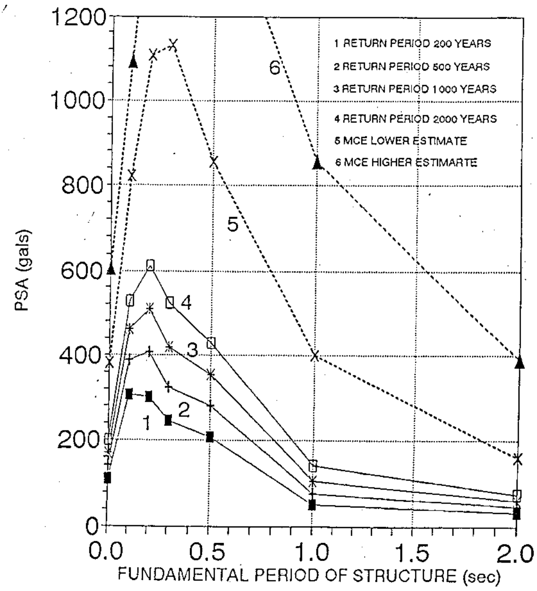

Fig. 6.27: **Preliminary design spectra, Kotli**

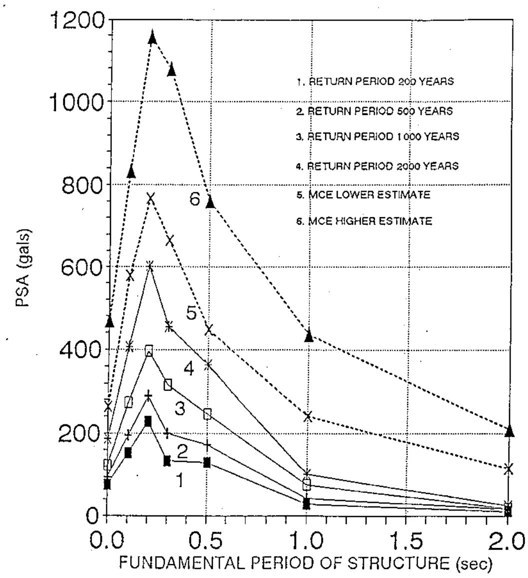

Fig. 6.28: **Preliminary design spectra, Allai Khwar**

To make use of the spectra, a design hazard level is selected and the corresponding spectrum is used directly or else the level of interest is interpolated between two graphs. For a dual loading design, an Operating Basis hazard level is chosen along with another hazard level, say a MCE. The structural design is checked, at the corresponding frequency of vibration, under the two conditions: one at working stress and the other at strength condition or at ultimate condition. It is the structural engineer who decides the details.

The reader is reminded that all spectra in this report are to be considered preliminary until further work is performed in assessing the seismicity of the region.

6.5.5 DISCUSSION OF THE RESULTS

The results are discussed with the aid of Figure 6.29, which includes the average estimates of the graphs in Figures 6.24 and 6.25, one for each one of the two sites described in this document. To show examples of different seismic conditions, two hydroelectric projects in the described region have been included; Neelum-Jhelum in AJK located close to the Main Boundary Thrust and the Reshun Gol in Chitral, located in the vicinity of the Hindukush (N36.2 E72.1). Additionally, two cases of high seismicity from elsewhere in the world are shown superimposed.

Figure 6.29 shows how the seismicity in the Azad-Kashmir region is moderate compared to the superimposed cases. The lower of all is the Allai Khwar site. However, it is important to note that it is probabilistic assessment based on the seismic catalogs the one that is lower, not necessarily the maximum credible events. This case is not uncommon in places of "moderate" seismicity in close proximity to major faults whose quiescency has not been well assessed (and thus a conservative high magnitude estimate is present, as in our case, elevating the design loads at large return periods). See how the place labeled GT has a higher seismicity estimate at short return periods but having no major faults in close proximity it has lower upperbound PGA's than the Azad-Kashmir area under the current assumptions.

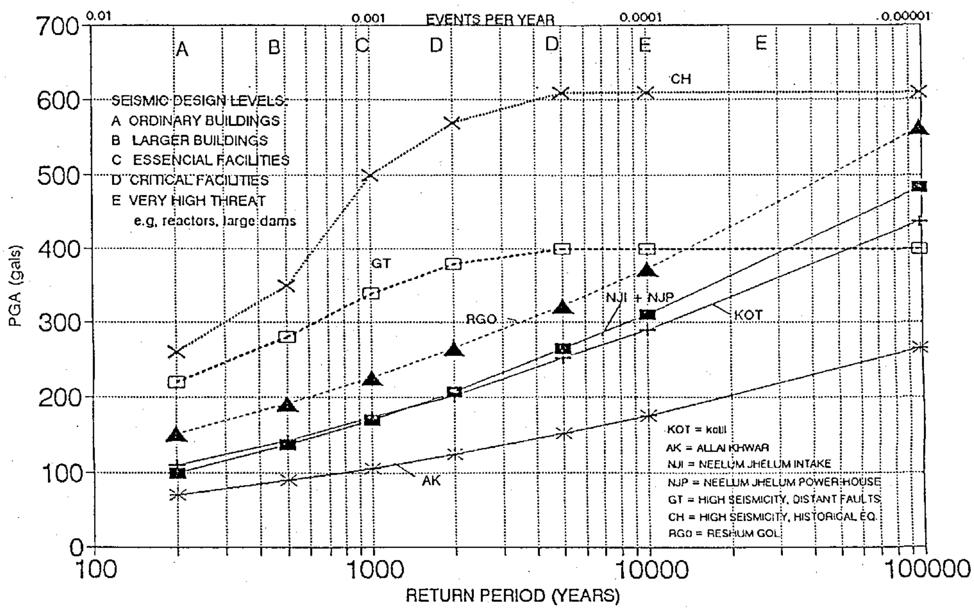

Fig. 6.29: **Peak ground acceleration – average estimates**

Supposing that the present evaluation is correct, the result means that in the long run less earthquakes may affect the sites but that several of those earthquakes that do occur, can be as strong and potentially damaging as those occurring at the places with a reputation of higher seismicity. In other words, while the Operating Basis Earthquakes may have lower demands, the design of very important facilities that should be protected against the Maximum Credible Earthquakes, regardless of probability, can be as critical as in places with higher seismicity rate.

The above underscores the importance of a good assessment of maximum credible earthquakes and good geological surveys and investigations. This should be a major task in further assessing the seismicity of any project area.

There are other potential biases in the results of probabilistic assessment based on seismic catalogs that one should be aware of. The problem is that in many parts of the world the available seismic catalogs are shorter than the potential return periods of damaging earthquakes. Thus, if such an earthquake has not occurred during the time span of the catalog, assessment will be depressed without anybody knowing it... until a string event hits the region. On the other hand, if such an earthquake did occur, and the catalog is shorter than the true return period, the recurrence assessment will be on the higher side. The recurrence will be overestimated.

The above underscores that probabilistic analyses may reflect average conditions, but average conditions do not necessarily set the trend to be followed. A good balance between average and extreme conditions is necessary.

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