PAKISTAN

WATER AND POWER DEVELOPMENT AUTHORITY

ATTABAD LAKE HYDROPOWER PROJECT

FEASIBILITY STUDY

VOLUME 4

NEOTECTONIC STUDIES & SEISMIC HAZARD ANALYSIS

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HYDRO PLANNING ORGANIZATION

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ATTABAD LAKE HYDROPOWER PROJECT
LIST OF VOLUMES

LIST OF ABBREVIATION

A

ADB	Asian Development Bank
AKCSP	Aga Khan Cultural Service Pakistan
AKDN	Aga Khan Development Net Work
AKF	Aga Khan Foundation
AKHS	Aga Khan Health Service
AKRSP	Aga Khan Rural Support Program

C `

CBM	Confidence-Building Measure
CBOs-	Community-based organizations
CPEC	China Pakistan Economic Corridor
DLP	Defect Liability Period

E

EIA	Environmental Impact Assessment
EL	Elevation Level
EMMP	Environment Monitoring Management Plan
EOT	Electric Overhead Bridge Type Traveling
EPA	Environment Protection Agency
EIA	Environmental Impact Assessment

G

GB	GilgitBaltistan
GEF	Global Environment Facility
GHG	Green House Gases
GLOF	Glacial Lake Outburst Floods
GSP	Geological Survey of Pakistan

H

ha	Hectare
HPO-	Hydro Planning Organization
HPP	Hydropower Project

I

ICT-	Information and Communication Technologies
IEE	Initial Environmental Examination
IRS	Indus River System
IUCN	International Union for Conservation of Nature

K

KKH	Karakoram Highway
KNP-	Khunjerab National Park

LIST OF ABBREVIATION

KPK-	Khyber Pakhtunkhwa
L	
LAA	Land Acquisition Act
LGO	Local Government Ordinance
M	
MASL	Meters Above Sea Level
MBT	Main Boundary Thrust
MKT	Main Karakoram Thrust
MMM	Mitigation Management Matrix
MMT	Main Mantle Thrust
MW	Mega Watt
N	
NA	Northern Areas
NCS	National Conservation Strategy
NEQS	National Environment Quality Standards
NGO	Non- Governmental Organizations
NOC	No Objection Certificate
P	
PAP	Project Implementation and Resettlement of the Affected Persons
PEPA	Pakistan Environmental Protection Act
PEPC	Pakistan Environmental Protection Council
PMAC	Program for Mountain Areas Conservation
PPC	Pakistan Penal Code
R	
RAP	Resettlement Action Plan
RNR	Renewable Natural Resources
S	
SC	Supervisory Consultants
SWHP	Surface Water Hydrology Project
T	
TOR	Terms of Reference
U	
UNDP	United Nations Development Program
V	
VO	Village Organizations
W	
WAPDA	Water and Power Development Authority

LIST OF ABBREVIATION

WCSDO	Wildlife Conservation and Social Development Organizations
WCS	Wildlife Conservation Society
WHO	World Health Organization
WUO	Water Users' Organizations
WWF	World Wide Fund

UNITS: CONVERSION FACTORS: SI TO FPS

Length	To convert from	to	Multiply by
	M	ft	3.281
	Cm	ft	0.0328
	Km	ft	3,280.84
	M	mi	0.0006214
	Km	mi	0.6214
Area	m^2	ft^2	10.764
	km^2	mi^2	0.3861
	m^2	acre	0.0002471
	km^2	acre	247.105
	Hectare	acre	2.471
Volume	m^3	ft^3	35.315
	m^3	US gal	264.172
	m^3	UK gal	219.969
	L	ft^3	0.035315
	m^3	Acre Feet	0.000810714
Velocity	m/s	ft/s	3.281
	cm/s	ft/s	0.03281
	m/s	mi/h	2.237
	km/h	mi/h	0.622
Acceleration	m/s^2	ft/s^2	3.281
Mass	Kg	lb_m	2.205
	Kg	ton	0.00110
Pressure and Stress	Pa or N/m^2	psi	0.000145
Discharge	m^3/s	ft^3/s	35.315
	L/s	ft^3/s	0.035315
	m^3/s	US gal/min	15850.3
	m^3/s	UK gal/min	13198.2
	L/s	US gal/min	15.850
	L/s	UK gal/min	13.198

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1 INTRODUCTION

1.1 GENERAL

Attabad Lake Hydropower Power Project (ALHPP) is proposed on Hunza River, a left tributary of Gilgit River. A large slide occurred on January 4, 2010 from right side slope of Attabad, chocked the Hunza River. The total height of the slide as estimated by GSP (Geological Survey of Pakistan) was about 100 m and the blocked length of river was about 2 km that destroyed 1.3 km of Karakorum Highway (KKH) (ISSMGE Bulletin: Volume 4, Issue 3 Page 21). Due to development of lake, WAPDA Authority planned to utilize this potential for Hydropower Development. Firstly, GB local consultants conducted feasibility study. The study was lacking in many aspects including geotechnical investigations, laboratory testing, layout planning, pros and cons of sliding, Neo-tectonic study and environmental issues. The Feasibility study has been submitted to Hydro Planning, WAPDA for comments and updating.

The Hydro Planning WAPDA entrusted to carry out the feasibility study of Attabad Lake HPP. During the detailed analysis and investigations, it is estimated that lake potential of 0.1MAF (125Mm^3), can be utilized to generate about 54 MW. The coordinates of weir site are 484036.834m E and 4018143.837m N with bed elevation 2368 m a s l from river bed**(DRW No: AFS- WR - 403)**

The proposed weir site is located about 20 km upstream of Aliabad (Central Hunza), near Attabad village, District Hunza. The site is accessible by metaled road from Gilgit city, the capital of Gilgit-Baltistan. From Islamabad, the site is reachable through Karakorum Highway (KKH) by covering about 750 km. It is also accessible through PIA air plane from Islamabad to Gilgit and thereon to Hunza via Karakorum Highway **(DRW No: AFS- GN- 102).**

Geologically site is located in Karakorum Block (KB) further North of Main Karakorum Thrust (MKT). The KB consists of Sedimentary, Metasedimentary, Igneous as well as Metamorphic Rock, throughout its extension from Karakorum Fault in the East, Chaman and Herat Fault in West (Zanchi 1993) ranging in age from Precambrian to Cretaceous. The overburden material, consist mainly of Angular Boulder Gravel with Sand and appreciable amount of fines (ABGM) and Rounded Boulder Gravels with Sand and appreciable amount of fines (RBGM). The talus deposits are main constituents of ABGM and well developed mostly in Shamshal valley and along Hunza River in upstream reaches. There are many evidences (the deposition of clayey silt along both banks of Hunza River) along the road indicate that the river might be chocked many time in recent past. Prior to Attabad slide, the slope failure occured at Salmanabad in 1958 and chocked the Hunza River.

The topography and geological conditions present in this valley indicate that it is glacial originated valley modified later on by river system. There are many glaciers that feed the Hunza River, from South to North i.e. Hassanabad, Gulmit , Gulkin , Passu and Batura Glaciers, from right side and Shamshal Valley Glacier from left side. Morphologically the valley is lithological as well as structurally controlled. Weak lithology i.e. slates as well as fault system attributed for the development of present shape of the Hunza valley in upper reaches and near MKT.

This Report is mainly based on the annotations observed during field visit at both banks along Hunza River and its tributaries mainly originated from glaciers. During this visit the main concentration was to observe the deformation in recent deposits mostly in rounded boulders gravel with sand and appreciable amount of fines (RBGM), sand, clay and silt etc. Due to chocking of river and development of lake, sedimentation took place at both banks of the river. As a result, of collision between Indian & Eurasian Plates, a continuous application of stress resulted in deformation of variegated levels.

1.2 SCOPE OF WORK

During the Feasibility Study, the colossal slide and as a result damping of Hunza River in 2010 has made the Neo-tectonic studies as core point. It is therefore, very important for the development of hydropower project in this area that understanding of Neo-tectonic setting should be explored to know the regional tectonic forces. Regional tectonic forces responsible for the massive slide, affecting Project Area severely as indicated by diverse features.

The area under study has covered by the two Nos of GT sheets 42 L/15 and 42 L/11 by Survey of Pakistan (SoP) at a scale of 1:50,000, covering the area upstream and downstream of slide mass.

1.3 OBJECTIVES

Main objectives are:

- Evaluation of the regional tectonic setting of the area and recognition of fault (regional or local) which may acted as a seismic source.
- Detailed investigation of the fault geometry, alignment, and structural deformations associated with these faults. These may include shear zones, fault bend folds, active slides and fault breccia.
- Recognition of active fault zones and their distinction from older, dormant fault zones.
- Assessment of the vulnerability of neo-tectonic activity along the faults/slides around the Project Area so that the movement along the affected area may be predicted.
- Identification of deformation/displacement in recent deposits to evaluate the activity commenced in the area.

1.4 METHODOLOGY

An array of activities including literature review, image analysis, field studies and data compilation are involved in Neo tectonic evaluation as per standard practices in Industry. These include:

- Collection of previous research on regional as well as on local geology, geomorphology and tectonics of Project Area.
- In-depth studies on satellite image analysis using GIS techniques by applying various image-enhancing techniques e.g. Digital Elevation Model (DEM) have been studied; the lineaments and faults on regional as well as on local scale have been recognized.

- Detailed geological map of the Project Site, regional and local faults within the vicinity covering the upstream and downstream of the Project Area have been marked on GT sheets at a scale of 1:15000 in the field to understand the trend of regional tectonic forces.
- During field visit keen concentration has been given to characterize the kinematics of faults where possible e.g. sense of faults (Strike and Dip), alignment and type of fault, throw and heave, dip direction and other associated characteristics.
- Development of fault-source map indicating various regional scale faults that may contribute seismic affect in the Project Area.
- The relationship of older tectonic features to the recent ones.
- Field evidences of Neo-tectonic features have been captured in Photos including active slides, tiltness in recent deposits, folding, faulting, step fault, fault associated folds in recent deposits, topographic features including drainage pattern at slopes and abrupt shifting of river/stream course.

2 REGIONAL GEOLOGY

2.1 GENERAL

Information and data relating to Regional Geology of Project Area is taken from already published literature and research papers. The catchment area lies in KB where snow covered peaks are quite common. The geological features in 40 km upstream and 50 km downstream of the Project Area have been studied in detail. In the Project Area many neo-tectonic features have been observed/recorded in the recent deposits which indicate that the regional tectonic forces are operating there.

The Project Area lies in the KB bounded in north by Central Pamir through Rushan Pshart Suture, in east by Karakorum Fault, in the west by Herat Fault and in south by Kohistan Island Arc (KIA) through MKT (Pashkov & Shvol'man, 1979 & 1981). The KB have classified as a part of Gondwana land in pre-collision history. The rocks of KB have stratigraphic association with rocks of Indian Plate as indicated by Paleozoic to Mesozoic sequence of both plates. It is likely to be considered that Karakorum Micro Plate and Indian Plate were united till Mesozoic Era.

The stratigraphic sequences of the Karakorum Plate are metamorphic equivalent of sedimentary rock in Indian Plate shows that both plates have pre-collision similarities. Also the Karakorum Plate consists of Sedimentary (well exposed in Chitral Area along Mastuj River), Ignoeus Rocks (Karakorum Batholith) and Metamorphic Rock (slates, schist and marbles).

The rocks of KB include a thick sedimentary cover, which is mainly Paleozoic in the western termination and Permian to Cretaceous in the central and eastern area. In the Hunza valley, the cover consists of a thick pile of Permian-Cretaceous sediments cropping out north of the Karakorum Axial Batholith (KAB). It separates the sedimentary cover to the north, named North Karakorum terrain by Searl (1991), from high to low grade metamorphic present south of the KAB just north of the MKT.

2.2 STRATIGRAPHIC SEQUENCE

The area under study mostly includes part of the Northern Karakorum Terrain, which comprises intensively folded and thrusted sedimentary rocks with a very low metamorphic imprint, locally reaching low grade conditions (Zanchi,1993). The Lower Permian to Upper Cretaceous succession of the North Karakorum represents one of the few terrains which escaped strong metamorphism during the Indian-Eurasian collision, thus permitted a detailed reconstruction of its stratigraphic framework **(DWG No: AFS-GE-291)**. Plutonic bodies mainly of mid-Cretaceous age intruded the sedimentary cover forming a discontinuous granitic belt developed about 100 km north of the KAB. Four main tectonic units have recognized in the Project Area (Gaetani et all., 1990). These include;

- Misgar Unit
- Sost Unit

- Gojal Unit
- Karakorum Axial Batholith (KAB)

The brief descriptions of these units are given below;

2.2.1 Misgar Unit

This unit consists mostly of slates, with few intercalations of metacarbonate quartzite and black terrigenous slates, mostly exposed at the Northern part of the Project Area. In some areas, its thickness increases up to thousand meter. It is strongly folded with intensive development of slaty cleavage. The fold axes generally trend E-W up to the Khunjerab Pass, where they turn to NNW-SSE. The unit has low grade metamorphism indicated by chlorite, biotite, and muscovite. This unit is intruded by granitoide pluton in northern and eastern terrain having western extension up to Sost. This unit belongs to different stratigraphic formations of Paleozoic age.

The southern boundary of Misgar Unit is faulted with south vergent thrust plane, the northern fault stacking the Misgar Slate over Jurassic limestone and sandstones of Sost belt (Gaetani et al. 1990). Large recumbent folds present along the northern flank of the Chapursan valley suggest southward movement of Misgar Unit.

2.2.2 Sost Unit:

It consists of grey to dark grey slates, meta-limestone, and quartzite. At places, it has dolomitic patches (Gojal Formation). Some sandstone beds with slate intercalations overlain by argillaceous limestone (Gircha Formation) with some sandstone, siltstone, limestone and dolomites of Lupghar Formation, Panjshah Formation, Lashkargaz Formation, ranging in age from Middle to Late Permian.

It comprises of thick pile of folded and thrusted sheets forming in the whole antiformal stack, later disrupted by strike-slip faults. The unit is bounded by two major faults, the Upper Hunza Fault (Desio, 1979) to the south-east and the Northern Fault to the north. Complexity of the tectonic pattern often prevented the reconstruction of continuous stratigraphic successions, as in the Middle Late Jurassic sediments. Fold axes and fault striations along the main thrust surface generally indicate a N-S compression. The well-developed schistosity is defined by sericite, muscovite and fine grained biotite with occasional occurrence of epidote and chloritoid. This suggests that low grade condition of metamorphism with an important increase of temperature with respect to other thrust sheets of the Sost Unit. These shear zones are still poorly understood and may possibly be related to the eastward prosecution of Hunza Fault juxtaposing the Gircha Slates of Gojal Unit to analogues metasediments of Sost Unit. The stratigraphic succession present in the Sost Unit spans from Permian to Late Cretaceous.

2.2.3 Gojal Unit:

This tectonostratigraphic unit was defined by Gaetani et al. (1990) and includes the sediments lying between the KAB and UHF. It is composed of two units, a terrigenous unit (Passu Slates) below and a calcareous-dolomitic unit above. In the lower Shamshal valley, dolomitic marbles terminate along a subvertical NS trending fault while southward this unit is intruded by KAB.

Contact metapelites generally undeformed or poorly deformed intrusive that grades into biotite, muscovite, and andalusite. folds within the unit trend from NW-SE to NNW-SSE and are generally NE-facing. Thrust planes show the same trends and are NE-vergent, as in case of (UHF).

2.2.4 Karakorum Axial Batholith (KAB):

The KAB crops out along the southern part of the studied area, where two major plutonic complexes were recognized, the Hunza and Batura Units (Debon et al., 1987). The Hunza Unit consists in a huge plutonic unit extending for more than 250 km, made up of medium grained granodioritic in composition, locally recrystallized. They represent a calc-alkaline association. mafic enclaves of various sizes are abundant and a conspicuous network of Cenozoic leucocratic dykes is locally present.

The Batura Unit intrusive, spanning in age from Paleocene to Eocene, is mostly new, as well as the findings of plutonic bodies belonging to this unit in Upper Chapursan Valley. The Batura Unit includes two main intrusive; The Kuk and Sarbzea Pluton.

The Kuk Pluton consists of pinkish, undeformed and unfoliated granitoides of various grain sizes, locally with porphyritic, microgranular and rapakivi textures. The Sarbzea Pluton mainly differs from the Kuk Pluton by its very coarse to medium grained rocks, which were deformed at places.

2.2.5 Ganesh Formation:

This Formation consists of pelite-psammite turbidite unit and overlying calc-pelite marble unit and are intercalated with each other. These units are metamorphosed up to upper amphibolite facies and therefore have well developed sheets of amphibolite. The Formation has well developed ruby and spinal. Different mines are also established in this Unit as can be observed along road near Ganesh Bridge.

2.2.6 Hassanabad Granite:

It is well exposed in the Lower Hunza valley and consists mainly of lower s-type granitoid-migmatite complex with metasedimentary enclaves. These garnet-tourmaline bearing two mica granitoids and migmatites are well exposed in Hasanabad Nullah and in Hunza valley along Hunza River.

2.2.7 Chalt Formation:

It consists of dark grey quartz biotite schist with subordinate quartz, marble and conglomerate. It is exposed along overturned anticline and faulted against Dumordo Formation. Permo-Carboniferous age is assigned to this Formation.

2.3 REGIONAL TECTONICS

Before the Northward flight of the Indian Plate, small continental pieces (Cimmerids, i,e. Karakorum Block, Helmad Block, Hasha Block etc) were broken up from the Northern edge of

Gondwana Land and welded with the southern edge of Eurasian Plate, consuming the old Tethey and opening the Neo Tethey, (Tapponnier, 1975, 1977; Molnar, 1977a).

In general, due to the subduction of the oceanic part of the Indian Plate beneath the Eurasian Plate, the Island Arc emerged in Middle Cretaceous age. The Arc Complex consists of calc-alkaline plutonic rocks mainly mafic in nature. The presence of blue schist metamorphism in Swat and Shangla Area indicates the trench environment.

The collision of the Indian and Asian Plates has been described as a "head on" north-south collision (Shackleton and Ries, 1984). This is generally accepted by many workers to have occurred in Eocene times (55-40Ma) (Powell, 1979; Klootwijk et al, 1979; Dewery et al, 1988; Treloar and Coward, 1991; Serrle et al, 1987, 1988). The terminal collision between Indian and Asian Plates is suggested to have occurred between 45-40 Ma (Molnar and Tapponnier, 1975; Klootwijk et al, 1985). It is generally agreed, however, that by 55 Ma, the Kohistan Island Arc was already sutured to the Asian Plate, probably since the Late Cretaceous, forming the MKT zone. This is confirmed by the presence of 85-80 Ma thermal event at this time (Treloar and Rex, 1990).

The rocks of Shyok Suture Zone (SSZ) are interpreted to represent the tectonised remainder of a marginal basin. The closure of the marginal basin occurred at the Eocene-Oligocene time boundary, and crustal shortening was responsible for generation of Neogene 2-mica granites of the KAB and regional metamorphism of the Pangong Tso Group (V.C Thakur, D.K. Misra, 2007).

The collision between the Indian Plate and Kohistan Island Arc is recognized as when the Tethyan Ocean disappeared and the continental masses docked. Following features recognize the main arguments for the Eocene age of collision: -

- Sediments deposited on the northern margin of the Indian Plate being of Eocene age.
- Subduction of the oceanic crust stopping, as recognized by the end of calc-alkaline magnetism north of the Indus Suture.
- The Blue schist facies are not developed along MKT zone showing the collisional belt.
- Slowing down of the Indian Plate motion, as recognized by magnetic anomalies.
- After collision, continued suturing occurred, associated with a 35˚ anticlockwise rotation of the Indian Plate relative to Eurasia. As a result of collision, mighty mountain ranges of Himalayas were developed having Island Arc Sequence in the north.

There are some topographic observations about the Himalayas that were immediately noticeable:

- The general curvature of the mountain chain.
- The mass of high land behind the mountain belt (Tibetan Plateau)
- The lineament of the high peaks confined in a rather smaller area.

This seemingly simplified chain becomes very disturbed, with a complete loss of these features in the Northern Himalaya. The general curving of the Higher Himalayan peaks and the suture around angles of some 180˚ is related to the structural anomalies that are present in Northwestern Himalaya: i.e. the syntaxes (Nanga Parbat Syntaxis, Hazara-Kashmir Syntaxis etc). These are absent in Central Himalaya. This shows that the collision between two plates is not a simpler phenomenon but there was a much greater extent of deformation to which the collision was accommodated. The accommodation was not constant, but suggested to be partitioned with different mechanisms occurring in different places of the orogenic belt.

Anticlock wise rotation of Mega Lhasa followed the Late Triassic docking of the Iranian Spur, using the later as pivot. The rotation was completed during the Middle Jurassic, when SE Pamir, Shaksgam and Karakorum joined the Qiangtang, more closely assembling Mega Lhasa as it approached the Asian margin (Maurizio, Gaetani, 2007). The Karakorum Block (KB) bounded in the east by Karakorum Fault, in the north by Rushan- Pshart Suture, in the west by Herat Fault and in south by MKT.

Structurally the KB is characterized by broad asymmetrical to tight, isoclinal folds which are commonly imbricated. A number of large regional scale thrust faults, e.g. the Tirchmir Fault, Reshun Fault, Baltit Fault, Upper Hunza Fault, Chapursan Fault and the MKT extends for a distance up to 100 km or more. The KB has undergone multiple deformation since the Cambrian. Parts of the KB have undergone at least four more deformations since the Kohistan-Karakorum collision from Paleocene to Pliocene.

After the collision, due to further Northward subduction of the Indian Plate, still active 4cm/yr, the stresses were accommodated by the imbricate thrust faults from North to South (Treloar et al, 1989). The collisional history along with metamorphic events trapped many clues between these fault systems. These are very useful to delineate the historic events and to unrivaled the movement of Indian Plate, collisional environment and modern deformational style.

2.4 REGIONAL FAULTS

The major regional faults of the region include, from north to south, the Main Karakorum Thrust (MKT), Main Mantle Thrust (MMT), Panjal Thrust (PT), Main Central Thrust (MCT), Main Boundary Thrust (MBT), Kashmir Boundary Thrust (KBT)/ Himalayan Frontal Thrust (HFT) and Salt Range Thrust (SRT) **(DWG No: AFS-GE-292)**.

Along with these regional faults, many local faults were developed to accommodate the regional stresses, these may be thrust fault or strike slip fault in nature. In most of the area many small scale strike slip faults are associated with the thrust faults to accommodate the deformation.

The general trend of these faults excluding MKT is predominantly east-west with change in trend due to syntaxial bends. The general description of these major faults is as follows: -

2.4.1 Karakorum Fault (KF)

Dextral Strike Slip fault of about 800 km long bounds western Tibet. The KF represents a much younger terrane boundary, juxtaposing rocks of the Ladakh and Saltoro Blocks to those of Karakorum terrane. U-Pb zircon age of leuco-granites intrusion shows that it must therefore be younger than 15 Ma old. Movement on the fault displaces the sequence approximately 200-250 km to South Eastern Tibet where the regional rock sequence can be regained (Burtman et al. 1963, Srimal 1983). It merges at the confluence defining a triple point and three blocks; the Ladakh Block to the south, Saltoro Block to the northwest, and the K KB to the northeast.

A number of teleseismic events have occurred along the fault. Interpretation of seismic data from 1975 Kinnaur earthquake confirms right-lateral strike slip motion on this fault. Three events were recorded from K KF Zone at the head of the Nubra Valley, since 1980, recorded by portable seismic stations, established by International Karakorum Project (IKP). It is seismically an active fault.

2.4.2 Upper Hunza Fault (UHF)

It is east west trending thrust fault that runs along the depression formed by the Chapursan and Upper Yarkhun Valleys (Zanchi 1973, Kazmi 1979b, Gaetani ey al. 1995). In this region it runs parallel to the northern margin of the KAB. Southeast of morkun (Upper Hunza) three teleseismic events of magnitude 5-7 and focal depth of less than 50 km have been recorded. These epicenters form a cluster very close to the mapped trace of the UHF. It means that the northern and western margin of the KAB is characterized by active zone of faulting along upper Hunza-Reshun Fault zone.

2.4.3 Main Karakorum Thrust (MKT)

The MKT is a low angle mega-shear with strike slip component, which on eastern side passes through Machlu in Hushe Valley, Shigar Valley, Zuhri Brook in Shyok Valley and Chalt in Hunza Valley extends westward through Ishkuman, Yasin and Shishi Valleys **(DWG No: AFS-GE-292)**. Its general trend swings between E and E-NE at low to medium dips towards the north. It is believed that this fault is seismically active.

2.4.4 Main Mantle Thrust (MMT)

The MMT, which is aligned with the Nanga Parbat-Haramosh tectonic line on east, span an area of about 400 km through Diamir, Kohistan, Swat, Dir and Banjaur, before entering Afghanistan **(DWG No: AFS-GE-292).** The general trend of MMT is NE-SW. It is located along the contact of the mafic/calc-alkaline meta-igneous rocks and the meta-sediments belonging to the Indo-Pakistan Continental Mass. Along this megashear near Jijal Village on Indus River (right bank), the igneous rocks have overthrusted the meta-sediments to the south over a 10-15 km wide zone. The thrust also manifests as the broad high topography of Kohistan relative to the Hazara adjacent to the south. In addition, numerous auxiliary fractures are developed and across the thrust frequent brecciation and mylonitization are also present along the contact. It is seismically active fault.

3 SITE GEOLOGY

3.1 GENERAL

The Project Area lies in KB north of MKT. It is V-shape valley, originated by glacier and modified later on by Hunza River. It is stratigraphically as well as structurally controlled. The 2nd highest peak of the World K-2 lies in this range. The rock units comprise granitoides with pellite and psammite sequence ranging in age from Paleozoic to Cretaceous.

3.2 TECTONOSTRATIGRAPHIC MAP

The Neo-tectonic studies are carried out on enlarged SoP GT sheets at a scale of 1:15000 during site visit. Different tectonostratigraphic units have identified and marked on these sheets and presented as drawing **(DWG No: AFS-GE-318 to 320)** at a scale of 1:40,000. Different stratigraphic/geological units pragmatic have been marked and summarized below: -

3.2.1 Lithological Units

3.2.1.1 Soil Units

The recent deposits are the most widely spread soil units overlies the bed rocks. The slopes are covered with overburden having variable thickness. Terrace deposits comprise mixtures of clay, sandy silt, boulders and gravel in various proportions. These units are mostly present in Aliabad, Karimabad, Nagar and Gojal Areas.

The soil units present in the Project Area are described below: -

3.2.1.1.1 Angular Boulder Gravels with Sand and Appreciable Amount of Fines (ABGM)

Most of the slopes are covered by material comprise ABGM. This is colluvial material broken from the rock units, rolled down slope and settled at the foothill or along the slopes.

These deposits are mainly associated with crushed/brecciated rock units, originated/caused by brittle deformation due to faulting/shearing at both sides. It has been modified by erosion/weathering and accumulated as ABGM at foothills, forming active slides, at both side slopes.

3.2.1.1.2 Rounded Boulder Gravels with Sand and Appreciable Amount of Fines (RBGM)

River bed is mainly occupied by RBGM. Some exposure is also present at powerhouse site near old Chinese Camp, Helipad Area. Due to formation of lake, the bed of the river is mostly covered with silt and sand extends up to Shishkat Bridge.

3.2.1.1.3 Terrace Deposits

Terrace Deposits consist mainly of mixture of clay, silt, sand and gravels with occasional boulders. These are mostly developed in loose material (RBGM, ABGM, Morainic and Breccia) **(DWG No: AFS-GE-302,305 & 309)** in all villages, depending upon the availability of water.

The irrigation channels were built in such a way that the irrigation demands are meted out by glaciers. In Central Hunza (Hyderabad, Aliabad and Karimabad) water is mainly fed from Ultar and Hassanabad Glaciers. Similarly, from Gulmit and Passu Glaciers, the channels were constructed to fulfill requirement of irrigation water.

3.2.1.1.4 Morainic Deposits

It consists mainly of material ranging in size from large boulders to clay size particles, angular to sub-angular, elongated and have flat surface **(DWG No: AFS-GE-299 & 302)**. The direction of elongation indicates the route of advancement of glacier. These are well exposed throughout the valley.

3.2.1.2 Rock Units

The main rock units exposed in Project Area explored during neo-tectonic study are as follows:

- Granitic Gneiss
- Granodiorite
- Passu Slates
- Marbles

It is 70 to 120 km wide and 1400 km long structural zone comprises the Karakorum Crustal Plate(KCP) which is one of the fragment of Cimmerian Collage derived from Gondwana Land and accerated to Eurasia. The stratigraphic history of the Karakorum is similar as that of Himalaya up to Cretaceous. The Project Site mostly present in the KAB consists of Igneous and Metamorphic rocks.

The brief description of the rock units are given below;

3.2.1.2.1 Granitic Gneiss

It is light grey to grey in color on fresh surface and weathers to light brown, coarse to very coarse grained, moderately to highly jointed, highly sheared up to higher elevation due to faulting, sparsely to moderately weathered, moderately hard to hard. It has well developed foliation with trending value N61ºW and plunging value 79ºNE. It is exposed at the right as well as at the left bank of the Hunza River. Some shear zones are also present within the Unit **(DWG No: AFS-GE-293 & 312)**.

On the basis of petrographic analysis, it is evident that the major constituents' minerals present in Granitic Gneiss are quartz, oligoclase, biotite while amphibole, chlorite, muscovite, epidote, and tourmaline are present as minor constituent minerals. The high percentage of Quartz grains show strong strain extinction, indicating that this unit has Alkali Silica Reaction (ASR) potential. The rock may therefore not be used as a coarse aggregate with Ordinary Portland Cement (OPC) or High Alkali Cement. It may be used with low alkali cement, slag cement or cement with additives likes fly ash, pozzolan. Some chemical additives like lithium nitrate or silica fume can also be used to control this reaction. The Schmidt Hammer values ranges from

35 to **45 MPa** indicating that rock is moderately strong to very strong. But in some shear zone where rock is tectonized locally, this value reduces up to **18-20 MPa**.

3.2.1.2.2 Granodiorite

It is dark grey to blackish grey in color, weathers to brownish grey, medium to coarse grained, moderately weathered, moderately hard to hard, moderately jointed intruded by pegmatite and granitic gneiss. It is foliated with trend and plunge values of N60ºW/79ºNE. Further downstream, it becomes light grey to grey in color, coarse to very coarse grained. It is crushed, mylonized, and sheared at places. It is well exposed at both banks where it is intruded by many pegmatite dykes. Some shear zones are also present in this Unit.

On the basis of petrographic analysis, it is evident that Granodiorite is quite dominate in the Project Area. The major constituent's minerals present in this unit are plagioclase, k-feldspar, quartz, biotite, and amphibole while Iron, muscovite, chlorite, and epidote are minor constituents. The high percentage of quartz grains show strong strain extinction, indicating that this unit has ASR potential. The rock may therefore not be used as an aggregate with OPC or High Alkali Cement or it may be use with low alkali cement, slag cement or cement with additives like fly ash, pozzolan. Some chemical additives like lithium nitrate or silica fume can also be used to control this reaction.

3.2.1.2.3 Passu Slates

It is well exposed at both sides of Hunza River, in upstream reaches of Hussaini village. It has intrusive contact with granitic gneiss/granodiorite. It is dark grey to blackish grey in color and weathers to brownish grey, fine grained, moderately weathered, weak to moderately weak, moderately to highly jointed but sheared at places, caused by different faults passing through this Unit. In or near the area of Borith Lake this Unit is highly crushed and sheared.

It has transitional upper contact with marbles exposed further upstream. In Shamshal Nullah, the slate is highly crushed and disturbed. On the basis of brachiopods and bryozoans, present in this unit, Carboniferous to Permian age is assigned to this Unit.

3.2.1.2.4 Marble

It is well exposed along Hunza River, near Passu village in upstream area. It is massive and crystalline dolomite. It is off white to greyish white in color, weathers to yellowish brown color, fresh, moderately hard to hard, moderately to highly jointed but sheared at places, caused by different faults passing through this Unit. Brecciated marble is well exposed along the KKH before Passu Glacier. In or near the area of Borith Lake this Unit is highly crushed and sheared / brecciated.

The high peaks of well renowned Passu Cones are developed in this unit. It has transitional lower contact with Passu Slates, the transitional lithofacies of marly limestone has well preserved fusulinid assemblage. On the basis of fusilinid present in this Unit, Middle to Late Permian age is assigned to this Unit.

3.3 GEOLOGICAL STRUCTURES

The Project Area tectonically lies in Karakorum Block. These units have undergone Karakorum as well as Himalayan Orogeny. The whole area has undergone/modified by two major fault systems MKT and Karakorum Strike slip fault. The MKT system which accommodated southward thrusting. Karakorum fault 800km long dextral strike-slip fault that bounds western Tibet, extending from the Pamirs to Gar Basin. As the Project Area has undergone multiple episodes of tectonics events, many regional as well as local faults and their splays have formed as discussed below.

3.3.1 Faults

Project Area has undergone compressional tectonic, resulted in release of energy forming thrust fault system with regional as well as local faults, bounded by MKT and Karakorum Strike Slip Fault (KSSF)**)**. These include:

- Batura Glacier- Hussaini Fault
- Borith Lake-Shamishal Nullah Fault
- Shishkat- Gulkin Glacier Fault
- Attabad -Hispar Valley Fault
- Central Hunza/Nagar- Chalt Fault
- Hassanabad Nullah Fault
- Hunza River-Nagar Fault

All these faults have been marked on the sheets and presented as **(DWG No: AFS-GE-318 to 320).** The dip and strike values of major faults have been plotted on the drawings.

4 NEOTECTONICS STUDIES

4.1 GENERAL

A large mass slided downward from right slope of Hunza River near Attabad village and chocked the River and destroy KKH for more than 2 km in January 2010. Chocking of Hunza River results in formation of a 25 km long lake up to Khyber village in Gojal Valley. Excavation work of channel through slided mass decreases down its level and span reduces upto Shishkat Bridge. Movement of huge mass downward is consequence of stress releases may have accompanied the direction of regional tectonic forces operating in this Region. To understand these regional forces and their effect and vulnerability of expected slope material to slide, Neo-tectonic study has been conducted.

This study covers the 40 km upstream and 50 km downstream of the Project Site along both banks of the Hunza River. Different features related to Neo-tectonics activity have been observed during site visit. In this study, particularly the focus has been to search the mode of deformation in recent deposits, along the both banks of river and its tributaries in nearby area.

The main objective of the Neo-tectonic study was to identify/observe the features of active tectonic events occurred in recent past about 0.1 Million years ago. There are many field observations regarding the Neo-tectonic activity. Some of the Neotectonics features/observation are given as under: -

- The tiltness in recent deposition, i.e. to study the slopes of gravels, clays, and sand layers w.r.t slope of the stream beds.
- Intersection of faults in recent deposits i.e. lacustrine deposits, terraces/ alluvial deposits or in any cultural features (houses, roads). The amount of displacement, Heave as well as Throw measurement, dip and strike of the fault.
- The presence of active slide zones.
- The displacement /uplift in fluvial as well as lacustrine deposits on each side of the lake/stream and magnitude of its displacement.
- Identify the zones of brittle as well as ductile deformation.
- To observe the movements along slicken sides / fault / joints blocks.
- The presence of escarpment slope along the planer area
- The presence of hanging valleys /cirques along main stream, in series and presence of waterfalls along it.
- Folding/bending in the recent deposits (alluvium, morainic, lacustrine).

A brief description of the right and left bank of the Hunza River has been described below: -

4.2 RIGHT BANK OF HUNZA RIVER:

Neo-tectonic features on the right bank of Hunza River in concomitant with different villages from upstream to downstream **(DWG No: AFS-GE-318 to 320)** are discussed below:-

4.2.1 Passu Village

Passu is one of the largest village in Gojal valley situated at the right bank of Hunza River along KKH about 35 km from Attabad Site. The great Passu Glacier, 56 km in length is present near the village. Many deformational evidences were observed in recent deposits along the road.

- 2-3 km Upstream of Passu Village

Co - ordinates

N	4038610.325 m
E	489292.583 m
El.	2470.03 m a s l

The coordinates have been measured by mobile topographer application.

A large deposit of RBGM material is present along the right side slope of the river along KKH. This material consists mostly of gravel, cobble, and pebbles with subordinate sandy material. Some inclinations in these deposits have been observed along roof and sole beds. This inclination varies from 15° to 35° layer-by-layer **(Photo 4-1).**

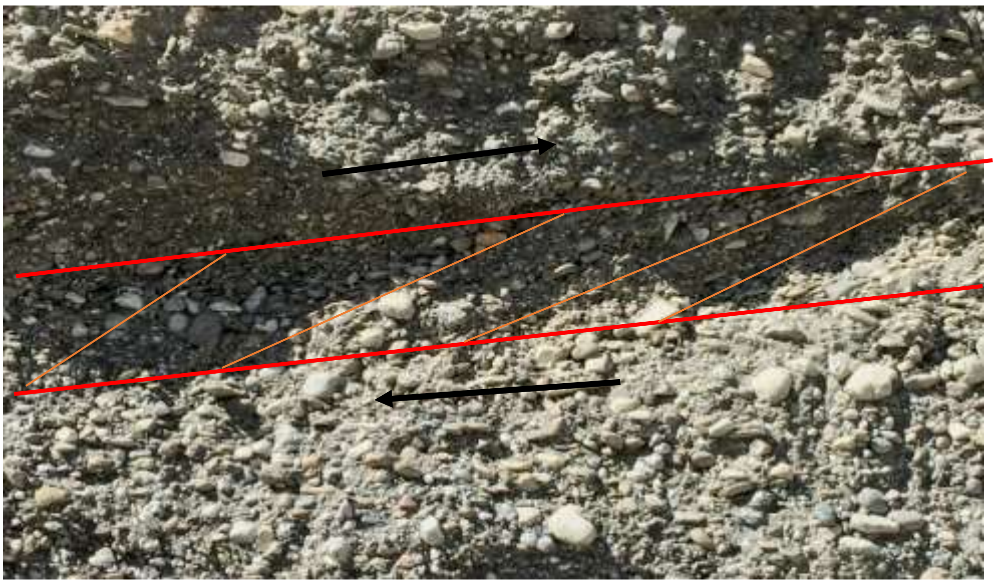

Photo 4-1 Inclined Gravel Layer Under Effect of Shearing

Some shearing effects have been chronicled along these planes in numerous layers. This shows that the area is tectonically active.

- In Passu Village

Co-ordinates

N 4039020.190 m

E 488598.996 m

El. 2521.0 m a s l

Further downstream, from previous station some clay deposits are reputable at right side slope in Passu village. Many Neo-tectonic features have been found in these deposits including jointing in recent clay deposits, folds, faults and associated structures, like tiltness in beddings.

Photo 4-2 Overall View of Clay Deposits and Inclination in Beds.

The clay deposit is overlain by morainic material of Batura Glacier. The clay deposits are tilted upward at an angle ranging from 10° - 15°. The area has undergone compressional regime, which uplifted the clay beds **(Photo 4-2)**.

Photo 4-3 Recumbent Fold Strata with Crenulation in Limbs in Clay Strata.

The clayey strata are folded with straight horizontal limbs and horizontal hingline. This shows that the horizontal compressional stress is applied on this material that turned this Unit into folded strata **(Photo 4-3).** Many micro folds (crenulations) in both limbs of fold are present. The hinge area toward outer layers is pointed out; showing intense compressional stress has been applied to the strata.

Photo 4-4 Stylolite/Pressure Solutions in Clay Strata.

The strata show some stylolite structures that are formed by expulsion of water through pressure solutioning. Alignment of wavelength and geometry of hinge area indicates that the compressional stress has been applied horizontally **(Photo 4-4)**. This shows that the recent stresses are functioning in this area.

Many joints are developed in the clay beds showing that there is relative movement in blocks along the plane, which might be acted as micro faults **(Photo 4-5)**. The relative movement of hanging wall block moved down relative to the footwall block, signposted the development of normal fault.

Photo 4-5 Micro Faults in Clay Beds.

At the same location there are cross cutting faults, dipping towards each other in clay beds. The block between two micro faults moved downward forming Graben structure while the block, that could not move formed Horst structure **(Photo 4-6)**.

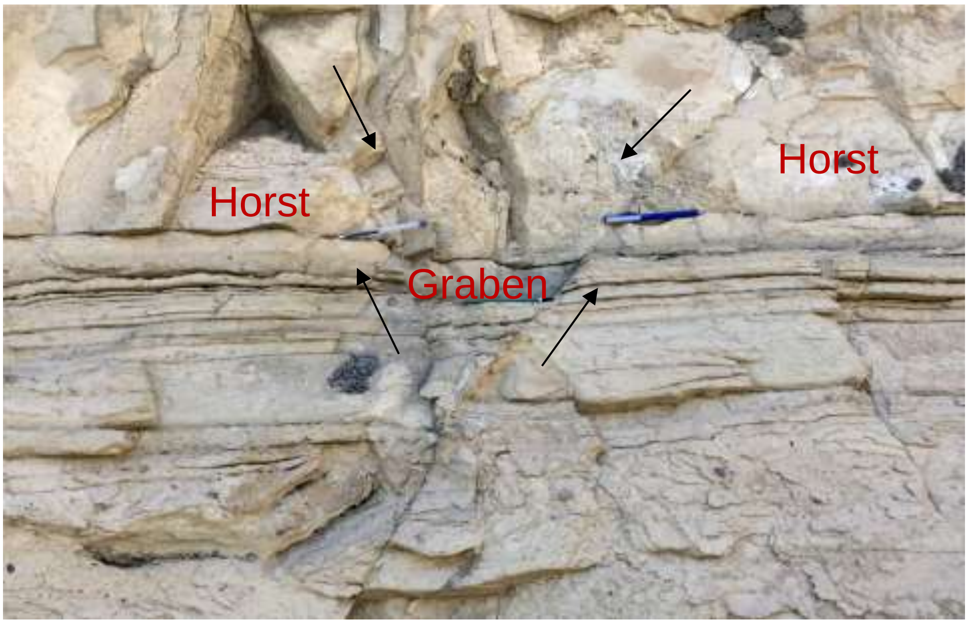

Photo 4-6 Horst and Graben Structure along Micro Fault in Clay Beds.

The formation of these structures in clay bed shows that there was relative movement along the micro faults in recent deposits.

The development of these normal faulting systems in such compressional regime indicates that these deposits have been under such environment where two thrust faults dipping toward each other. The up thrown block between these two faults undergone extensional regime where normal faults have been developed. This indicates that this area has been under active tectonics regime.

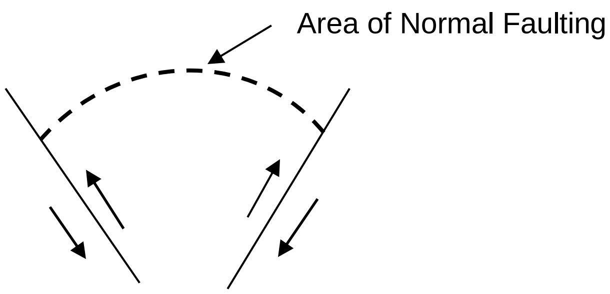

Figure 4:1 Development of Normal Faults under Compressional Regime.

Further, downstream, highly sheared marble and graphitic schist is exposed along the KKH. Highly sheared rock is cropped out up to high elevations and are accountable for the rolling down of boulders downward. Many active slides are instigating from this brecciated / sheared rock **(Photo 4-7)**, showing that this area has been under recent tectonic active stress.

Photo 4-7 View of Active Slides in Passu Village.

In Passu village, there is a large shear zone along which the bedding joint have shear movement in marble. The shear zone is tilted inward **(Photo 4-8)**.

Photo 4-8 View of Bedding Joints along Shear Zone Passu Village.

This shear zone extends up to active slides and disappears. Highly sheared rock formed due to intersection of different faults are accountable for wide valley section.

4.2.2 Murradabad/Barut Village

Coordinates

N	4034396.199 m
E	491392.588 m
El.	2564.02 m a s l

The Muradabad village has large cultivated terraces, irrigated by glacier water as well as by River. These terraces are developed on morainic material deposited by Passu Glacier.

In nearby Muradabad village just downstream of Passu village, a large morainic deposits of Passu Glacier is present along road. These morainic deposits are deformed due to release of compressional stress. The original deposited layers of boulder and gravels are allied and tilted up at an angle of 18° **(Photo 4-9)**.

Photo 4-9 View of Bedding Joints along Shear Zone Muradabad Village.

In this morainic deposit, folding in some clay layers are pragmatic. These folds are of small scale with minimum amplitude also the material is vertically jointed **(Photo 4-10)**. All these features indicate that the area is under regional compressional active stress.

Photo 4-10 View of Micro Folding in Clay Beds near Muradabad Village.

4.2.3 Road section from Muradabad to Hussaini Village:

Co-ordinates

N	4033080.557m
E	489417.275m
El.	2656.69m a s l

Just upstream of Hussaini village a large mass of ABGM and brecciated rock is exposed along the road. It is present in the alignment of thrust fault where crushed marble is in contact with Passu Slates. The faulted contact between slate and marble is well exposed along road **(Photo 4-11)**.

Photo 4-11 View of Brecciated Rock Upstream of Hussaini Village.

In this area two faults are intersecting each other, one is striking N60°E and dipping 40°NW while other is striking NW and dipping NE **(DWG No: AFS-GE-318)**. Due to these faults discrete hillocks have formed with thin overburden overlain by fault breccia. At few feet away from breccia, a slided material consists of ABGM is present along road. Apparently this material seems to be stable but in excavated portion, this material is folded. Compressional forces are responsible for this deformation exposed at slope **(Photo 4-12)**.

Photo 4-12 View of Folded ABGM Just Upstream of Passu Village.

Rock (Passu Slates) is locally folded, some shear joints along which the cleavage plane (originally bedding planes) across shear joint has different dip values. The overall strike of slates is NW and dipping in NE. but along this shear joint some movement took place and the value of dip changed from SW to NE **(Photo 4-13)**.

Photo 4-13 Change of Dip along Shear Joint.

Change of sense of dip along the shear joint shows that some shear forces have been active in the area. The development of such joints indicate the brittle deformation style.

4.2.4 At Hussaini Village

Coordinates

N 4031462.478 m

E 488964.085 m

El 2413.46 m a s l

At Hussaini village, thick deposit of RBGM is exposed at right bank of river, upon which terraces formed. The sand beds in this material are tilted at an angle of 25° **(Photo 4-14)**. Joints are developed in it shows that this deposit has undergone stress.

Photo 4-14 Inclination in Sand Beds in RBGM.

The gravels are compacted and exposed vertically owing to overburden pressure and breaks in blocky form. The gravels beds are tilted up from river at an angle ranges from 6° to 11° but at places it is inclined at an angle of 25° **(Photo 4-15)**.

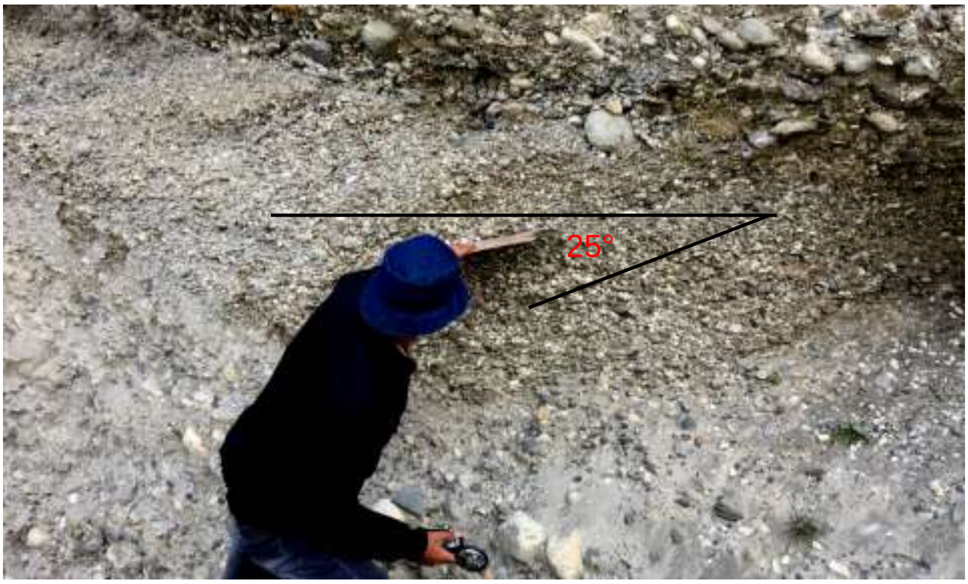

Photo 4-15 Inclination in RBGM.

This inclination in gravel bed indicates the effect of active shear forces operative on recent deposits and responsible for inclination in RBGM.

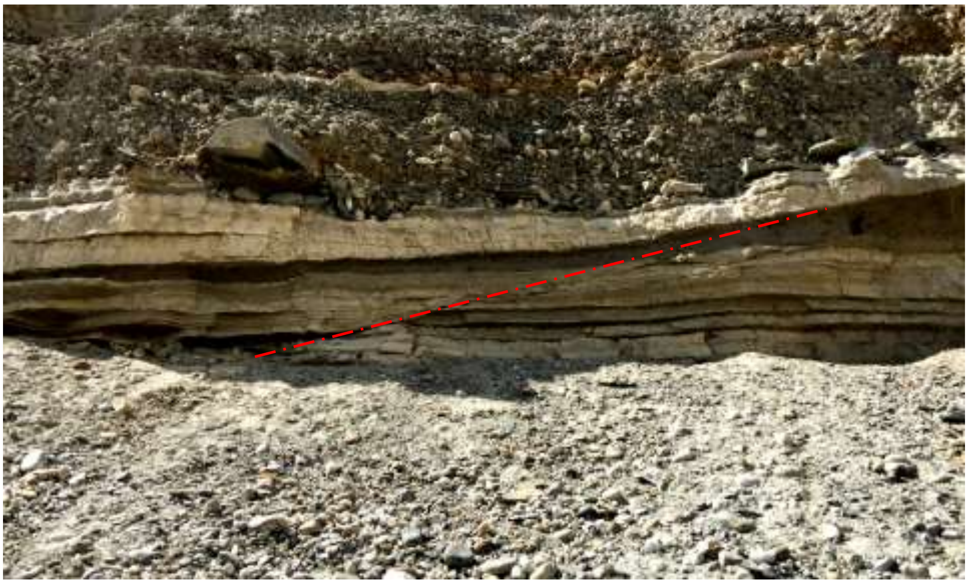

Photo 4-16 Micro Fault in Clay Deposit Overlain by RBGM.

A micro fault is observed in the clay deposits that cut the clays, perishes in RBGM, striking at N76°W and dipping 35°SW. The conglomeratic bed have pointed upward gravels, indicative of uplifting of deposit **(Photo 4-16)**.

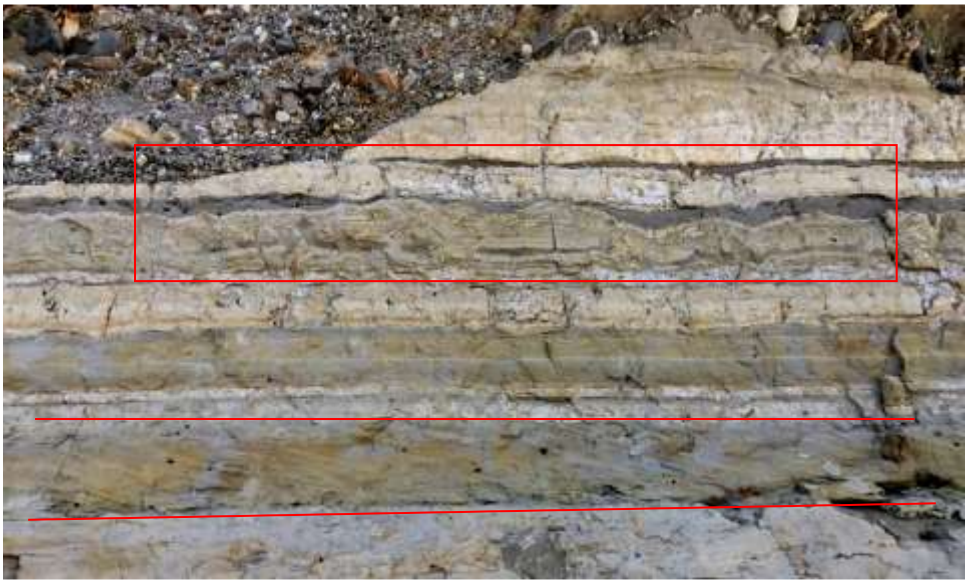

Photo 4-17 Micro Folding and Inclination in Clay Deposit Overlain by RBGM.

The highlighted lower portions in **(Photo 4-17)** indicate angularity in beds, tilted upward against the river flow direction. It shows that uplifting took place during deposition of these beds. Some compressional forces have been functioning which are accountable for evolution of micro folding in this strata. This intense deformation might be due to the compressional stresses operational in this area due to presence of active fault **(DWG No: AFS-GE-318)**.

4.2.5 Way from Hussaini to Borith Lake:

Along the track from Hussaini to Borith Lake, sheared slates has intrusive contact with granitic gneiss. Some clay deposits are also present at higher elevations along road toward Borith Lake.

Photo 4-18 Contact of Granitic Gneiss and Passu Slates.

The slate is highly sheared/crushed and easily erodible. Micro folding and faulting along with jointing is observed in this deposited. The tiltness in beds is quite common **(Photo 4-18)**. These beds are tilted at an angle of 12° with horizontal surface.

Photo 4-19 Micro Faults in Clay Beds.

It is clear in above Photo that the sandy and clayey beds have movement along fracture planes. The hanging wall block move down relative to footwall forming normal faulting **(Photo 4-19)**.

Photo 4-20 Fold in Clayey Silt along Trace to Borith Lake.

The folded strata in ABGM indicate that the area is under compression and stress are active in recent deposits **(Photo 4-20)**.

4.2.6 At Borith Lake:

Coordinates

N	4032452.941 m
E	487686.816 m
El.	2682.49 m a s l

At higher elevation from main KKH, a large lake of salty water is present. The alluvium material comprised of RBGM and sand has faulted contact with Passu Slate. Fault may be responsible for alluvium material to move up to the higher elevation. During the detailed study of area, different neo-tectonic features have been observed which are given below,

- Highly deformed sand and gravel beds.
- Tiltness in sand beds having inclination ranges from 15° to 25°.
- Cross bedding in sand beds.
- Folded strata.
- Pinching of sandy beds.
- Half fold.

Photo 4-21 Highly Deformed Sand and RBGM.

The strata are highly disturbed and uplifted to high elevation by fault. Due to tectonic uplift different deformation phases have been observed in this deposit **(Photo 4-21)**. The deformational style shows that multidirectional deformational stresses are operational and responsible for deformation in recent deposits.

Sand beds in this area have tilted at an angle of 15° to 25°. The fault responsible for this is striking and dipping towards NE and NW respectively **(DWG No: AFS-GE-318).**

Photo 4-22 Inclination of RBGM and Sand Beds.

Photo 4-23 Inward Inclination(curvature) of RBGM and Sand Beds.

Some sand beds have X-bedding which indicates that the direction of flow of water changes reasonably from time to time which is well preserved in strata at site **(Photo 4-21, 4-22, 4-23)**.

Photo 4-24 X-bedding and Pinching of Sand Beds.

Some beds are pinching against bedding planes indicate that the direction of river flow change abruptly due to operational stress **(Photo 4-24)**.

Photo 4-25 Folding in RBGM and Sand Beds.

The above Photo indicates that the clay bed is folded showing the compressional environment. The tiltness of the bed is upward with lateral compression acting on the recently deposited strata.

It is observed during study that the lateral compression is operating in the Borith Lake area. The plastic behavior of clayey silt can be seen in folded strata where clayey silt is accumulated in hinge area of fold with increase in thickness of material (**Photo 4-25, 4-26)**.

Photo 4-26 Folding in RBGM and Sand Beds.

Photo 4-27 Folding in RBGM and Sand Beds.

Many micro folds can be seen **(Photo 4-27)** showing that this very coarse grained gritty sand with silt intercalations is folded under lateral compression. The degree of deformation is quite high and the direction of compression changes from time to time as indicated by box fold with two hinge lines with one limb further folded as highlighted in rectangle.

Associated with this folding, some dislocation of silty beds are also observed along fracture surfaces representing compressional regime as hanging wall moves upwards relative to foot wall forming thrust fault **(Photo 4-28)**.

Photo 4-28 Micro Faulting in RBGM and Sand Beds.

These dislocations of beds, folding, tiltness, X-bedding indicate that the area is under active compressional stress.

As moved further from Borith Lake toward Passu Glacier on kacha road, RBGM is present on both sides of the road. The schist present in rear area of Lake is quite sheared and the height of peaks reduces abruptly. Near the edge of Passu Glacier, the schist are in faulted contact with marble. The bedding planes of both blocks along the fault have different sense of dip **(DWG No: AFS-GE-318)**. The bedding of marble is trending N63°W and dipping at 39°NE while the schist is trending at N54°W and dipping at 78°SW.

Photo 4-29 Fault Breccia of Marble at High Elevation

Towards western slope of the Borith Lake, crushed marble is present at higher elevation. It is brecciated rock crushed by fault **(Photo 4-29)** and exposed as discrete units about 50 m above the water channel at slope. The coordinates of the breccia is

N	4032085.486m
E	487153.319m
El.	2771.47 m a s l

The depression had been originated by faults resulted to the formation of lake. The alignment of the fault is marked **(DWG No: AFS-GE-318)** along which no rock is present at track towards Hussaini village that confirms the presence of fault.

4.2.7 Just Downstream of Gulkin Glacier:

Coordinates

N	4029091.513m
E	488760.419m
El.	2445.0 m a s l

Near the Salvia Restaurant, just downstream of Gulkin Glacier along Hunza River, some alluvium material is present along the KKH. This alluvium is overlain by morainic deposit. Some tectonic features are well preserved showing movement in recent deposits along fractures. **(Photo 4-30)**.

Photo 4-30 Micro Fault in Alluvial Gritty Sand.

Formation of jointing pattern in recent deposits, and movement along these fractures is clear indication of active tectonic stresses.

Photo 4-31 X-bedding in Sand.

Along with jointing, there is X-bedding in sand deposits. It indicates that the tectonic uplift might have taken place or the direction of flow change **(Photo 4-31)** responsible for X-cutting of sand beds.

Photo 4-32 Folding in Clayey Silt with Pointed Hinge.

The clay layers in recent deposit are folded under lateral compressional force. The strata are disturbed and evident of Neo-tectonic activity **(Photo 4-32)**.

4.2.8 At Attabad Village:

A large slide moved downslope in January 4, 2010 forming a lake of about 25 km unto Khyber village near Batura Glacier. Pre-slided geological features indicate that Attabad village was situated on morainic material. The morainic material was underlain by granitic gneiss. The Attabad village was junction point of three faults **(DWG No: AFS-GE-319)** During surface geological mapping and neo-tectonic studies it is observed that fault "A" is along Hunza River, fault "D" has NE trending and another fault trending NW, merged at Attabad village **(Photo 4-33)**.

Photo 4-33 View of Fault Alignment Crossing Hunza River near Attabad.

The rock is highly sheared, fractured and intensely jointed due to tectonic activity. Blocks of rock slided down mostly due to wedge failure. The shear strength of the rock reduces due to Neo-tectonic activity / movement along fault and failure occurs **(Photo 4-34)**.

Photo 4-34 View of Attabad Slide.

Firstly, some cracks appeared on the surface in cultivated terraces, with the passage of time the fractures grew and became wider and wider, accelerated by Hydrological conditions. As a result of operational neo-tectonic forces and hydrological condition, failure occurred in the form of enormous slide.

Mechanically sheared material under influence of tectonic forces disturbed and moved downslope by accumulating in riverbed and completely demolished about 2km of KKH.

The rock in downstream vicinity of slide is also sheared with many shear zones at right side while at left side in downstream areas, rock is brecciated due to fault **(DWG No: AFS-GE-319)** The Attabad slide is still active, as indicated by rolling down of material can be observed along this slide. It indicates that it is tectonically active area with some stresses releases along junction point/faults from time to time.

4.2.9 At Sarat Village:

Coordinates:

N	4018254.850 m
E	481549.816 m
El.	2371.35 m a s l

As a result of Salmanabad slide in the year 1858, a large lake developed in upstream reaches. The depositional clayey silt can be seen on both bank of Hunza River. Due to operational neo-tectonic forces, deformation including folding, jointing, and micro faulting have developed in these deposits.

Both vertical and oblique joints can be seen in clayey silt at right side near Sarat Suspension Bridge. The strike and dip values of vertical and oblique joints are N38°W/87°NE and N32°E/63°SE respectively **(Photo 4-35)**.

Photo 4-35 View of Vertical and Oblique Joints in Clayey Silt at Sarat Village.

Clayey silt beds are striking N 80°E and dipping 18°NW **(Photo 4-36)** at the left side of road leading to Sarat Village while at the right side of the road these beds have strike N 32°E and dipping 9°SE **(Photo 4-37)**.

Photo 4-36 Tiltness in Clayey Silt Beds, Left Side of Road at Sarat Village.

The strike of the beds is NE while the dip is in opposite direction, indicating that it forms some sort of antiform. Formation of antiform in recent deposits clearly indicates that lateral shear compressional forces are operational in this area.

Photo 4-37 Tiltness in Clayey Silt Beds, Right Side of Road at Sarat Village.

Just downstream of Sarat Village near the suspension Bridge, fault breccia is exposed along the river showing the alignment of fault.

Photo 4-38 Folded and Sheared Clayey Silt at Sarat Village.

Photo 4-39 Sheared and Smeared Clayey Silt at Sarat Village.

Photo 4-40 Fault Breccia just D/S of Suspension Bridge at Sarat Village.

Folding, jointing, smearing and shearing of clayey silt **(Photo 4-38, 4-39, 4-40)** deposit show some lateral stresses are actively operating in this area. The active slides and rolling down of brecciated material from this slope indicate that it is tectonically active area.

4.2.10 At Salmanabad Village:

Coordinates:

N	4018373.023 m
E	479430.485 m
El.	2661.0 m a s l

It is situated downstream of Sarat village and accessible by unmetaled road. The whole village is founded on fault breccia having many exposures of gaugic and brecciated materials. It is present along the road with alluvium material consist of sand and RBGM.

Photo 4-41 Fault Breccia along Road at Salmanabad Village.

The fault is striking N20°W and dipping at 58°SW with some parallel shear zones. Alluvium material RBGM and sand lifted upward along the fault B and fault C up to this elevation and are in contact with crushed marble **(DWG No: AFS-GE-319)**.

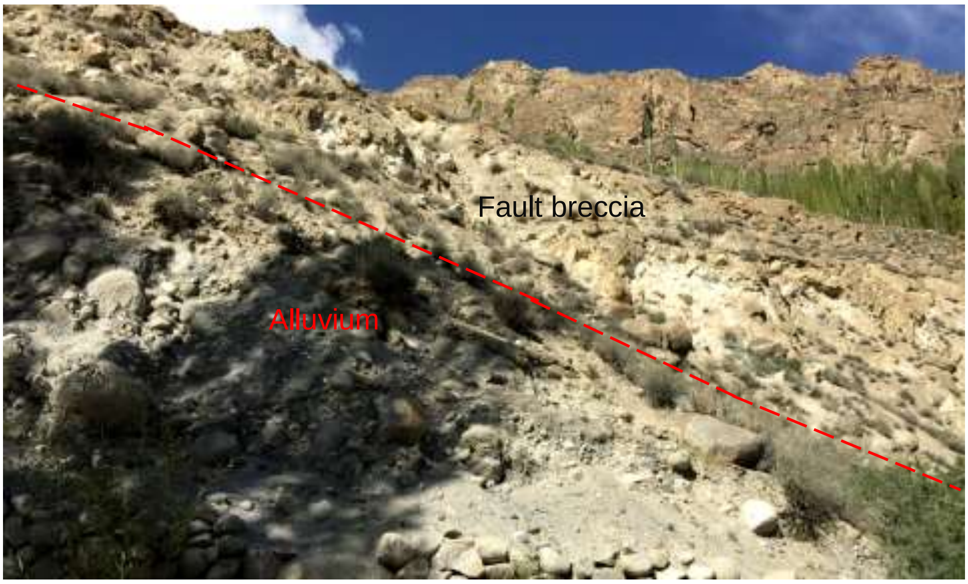

Photo 4-42 Faulted Contact of Breccia with Alluvium at Salmanabad Village.

As we move further up to higher elevations, the exposure of fault breccia and alluvium extend and well exposed up to elevation of 2704.02m **(Photo 4-41)**. Fault C is striking NW and dipping NE. Due to these two faults the whole rock beneath Salmanabad village is highly tectonized and crushed to the level of breccia and is well exposed along Hunza River **(Photo 4-42, 4-43).**

Photo 4-43 Fault Breccia beneath Salmanabad Village along Hunza River.

4.2.11 At Hassanabad Nullah:

Coordinates

N	4018015.083m
E	462346.127m
El.	2216.92 m a s l

At the nullah mouth, a shear zone trending NE and dipping NW sheared the rock and turned it into breccia. Micro folding, crenulation and isoclinal folding is quite common. The slopes are unstable with rolling down of boulders is quite common **(Photo 4-44)**.

Photo 4-44 Active Slides at Right Side Slope of Hassanabad Nullah.

The presence of active slides in the area is an indication of active tectonic forces.

Photo 4-45 Fault Breccia/Gauge along Road Just D/S of Murtazabad Village.

Just D/S of Hassanabad Nullah's confluence with Hunza River, along KKH, fault breccia of yellowish brown, reddish color, is exposed. A hot spring seepage is associated with this fault. A number of active slides have been activated along this fault. This fault extends further downstream and exposed in Nasirabad (Hindi) where a number of active slides are associated with this fault **(Photo 4-45)**.

4.2.12 At the Murtazabad- Shahyar Bridge:

Further downstream of Murtazabad toward Shahyar village, thick exposure of clayey silt is exposed along the road near the bridge. The beds are tilted inward, at an angle of 20° to 22° **(Photo 4.46)**.

Photo 4-46 Inward Tiltness in Clayey Silt Just D/S of Murtazabad Village.

Hummocky X-bedding is quite common in this deposit, formed under wave action with huge load under depth of water **(Photo 4.47)**.

Photo 4-47 Hummocky X-bedding in Clayey Silt near Murtazaba Village.

The whole deposit is jointed vertically along which falling of blocks is quite common.

4.3 LEFT BANK OF HUNZA RIVER

4.3.1 At confluence of Shamshal Nullah with Hunza River:

Coordinates:

N	4039351.149m
E	490847.707m
El.	2522.91 m a s l

Near the confluence of Shamshal Nullah at left bank, morainic deposit having clay layers is exposed. It is jointed and range from clay to morainic material **(Photo 4-48)**.

Along Upstream course in Shamshal Nullah, the Geological conditions become worst. The left side of nullah is highly crushed responsible to generate many active slides, associated with active fault system. Passu Slate is highly crushed/tectonized, sheared and folded, near the confluence of Shamshal Nullah with Hunza River **(Photo 4-50)**.

At right bank of Shamshal Nullah, many active slides originating at higher elevation from Passu Cones deposited their load in foothills. The rocks are highly crushed up to higher elevations at both sides of Shamshal Nullah due to intersection of two faults, one is running from Borith Lake while other is running from Batura Glacier **(DWG No: AFS-GE-318)**

Development of joints in morainic material, active slides, highly sheared and folded strata **(Photo 4-49)** show that the area is tectonically active.

Photo 4-48 Jointing in Morainic Material, near Confluence of Shamshal Nullah with Hunza River.

Photo 4-49 View of Active Slides in Shamshal Nullah.

Photo 4-50 View Of Folding, Crushed Rocks and Active Slides in Shamshal Nullah.

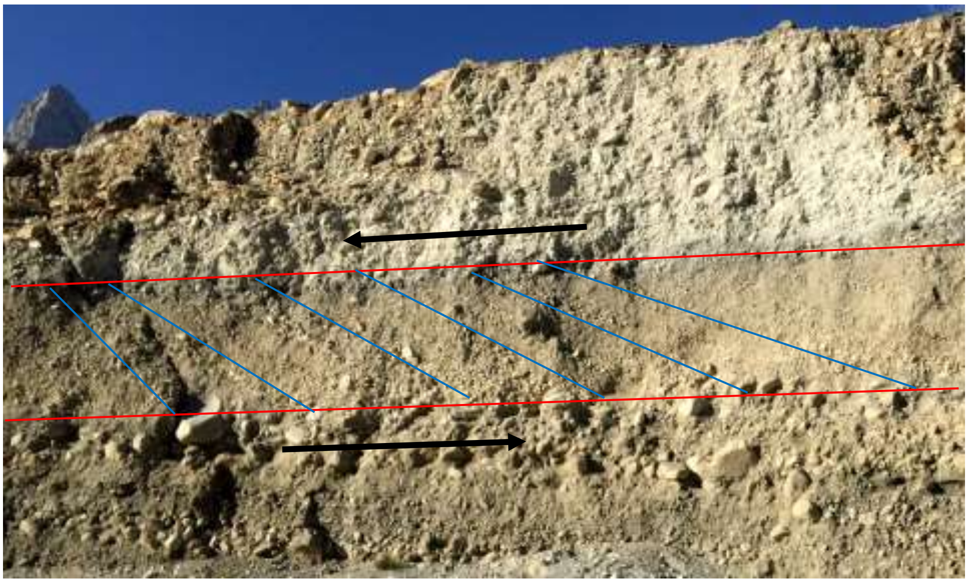

Photo 4-51 View of Inclined Gravel Bed Near Confluence of Hunza River and Shamshal Nullah.

Near the bridge at left bank of Hunza River, RBGM is exposed. The degree of inclination of these beds range from 15° to18° **(Photo 4-51)**. Some compressional shearing forces resulted inclination in these beds. Inclination along specific beds, packed by horizontal layers indicates that shearing force is operative along these layers.

4.3.2 In front of Gulmit and Gulkin Glacier:

Geological condition in this area is quite poor. A fault with strike and dip values N14°W and 42°NE respectively, **(DWG No: AFS-GE-318)**, crushed the rock into breccia. Whole rock unit disintegrated and accountable for rolling down of large boulders downwards forming active slides. The rolling down of rock pieces from higher elevation shows that some active tectonic forces are affecting on this slope and make it unstable **(Photo 4-52)**.

Photo 4-52 View of Active Slides along Left Bank of Hunza River.

Further downstream, a fault passes through Shishkat village. The left side gradient becomes highly disturbed because of crushing of rock. Terraces of Shishkat village on breccia were formed by this fault.

4.3.3 In Perennial Nullah at the end of Tunnel 4:

Coordinates:

N	4019140.03m
E	489442.982m
El.	2482.0 m a s l

At the end of Tunnel 5, a perennial nullah is present. In this nullah about 600m upstream, fault breccia is exposed **(Photo 4-53)**. This nullah seems to be developed along large shear zone; originated from this fault, which is bounded by hard rocks on both sides. This fault / shear zone crushed the rock into breccia and responsible for the bending of Hunza River at 90°. This fault crosses the river and is responsible for active slide on right bank of river **(DWG No: AFS-GE-319)**.

Photo 4-53 View Of Fault Breccia in Perennial Nullah.

4.3.4 Inside Tunnel 2

Many cracks/joint are going to develop in the concrete especially in crown area in Tunnel-2. The pattern of the cracks indicates stress release and shear oblique joints **(Photo 4-54)**.

Photo 4-54 View of Recently Generated Joints in Tunnel-2.

As far as geological conditions are concerned, this portion of tunnel in is under influence of two faults **(DWG No: AFS-GE-319)**. Rock is highly crushed, rolling down of boulders is quite common along these active faults. The active tectonic forces are responsible for the development of fractures in this terrain.

The same features can also be noted in concrete structure between Tunnel 2 and 3 **(Photo 4-55)** along KKH.

Photo 4-55 View of Recently Generated Joints between Tunnel-2 & 3.

The concrete slab fractured between Tunnel 2 and 3. It is evident that some tectonic forces are recently active in this area.

4.3.5 Between Tunnel 1 and 2

The area between Tunnel 1 and 2 is highly sheared **(Photo 4-56)** due to influence of fault with strike and dip values of N52°W and 50°NE. This fault is a splay of Hunza Fault **(DWG No: AFS-GE-319).**

Photo 4-56 View of Fault Breccia between Tunnel-2 & 3.

The rock is highly tectonized / brecciated. The extension of this fault is upto old KKH route and exposed in rear of old Chinese camp. The breccia with some gaugic material indicates brittle shearing responsible for originating active slides. Along the alignment of fault, two springs are present in this area.

4.3.6 Power House Area

In powerhouse area near helipad along old KKH, clayey silt is present where Chinese Camp was established. The clayey silt was deposited after river choking due to Salmanabad slide. Due to operational compressional stresses, some deformations including faulting, shearing, folding, and tiltness in clayey silt have been observed.

Photo 4-57 Micro Thrust Fault in Clayey Silt Beds near Helipad.

The relative movement of both blocks against fault plane indicates compressional environment, which moved the hanging wall block upward **(Photo 4-57)**.

Photo 4-58 Inclination in Clayey Silt near Sarat Village Bridge.

The clayey silt beds are well exposed at the left side of Hunza River near Sarat Bridge. The clayey silt beds are well jointed and tilted upward at an angle ranging from 10° to 15° **(Photo 4-58)**. The inclination of the beds are in recent soil is indicative of active tectonic forces.

Near old Chinese Camp, at powerhouse area, the clayey silt is folded **(Photo 4-59)**. Folding in recently deposited clayey silt might have resulted of slipping along fault plane under regional compressional shear forces which resulted in the formation of folding and faulting.

Photo 4-59 Folding in Clayey Silt near Helipad/Power House Area.

Near the SCO building, along old KKH, near Tunnel-1, some cracks are going to develop in recently deposited material. The development of joints is mostly parallel in nature but occasional cross cutting joints also present **(Photo 4-60)**.

Photo 4-60 Development of Parallel Joints near SCO Building.

4.3.7 In front of Salmanabad and Ahmadabad Village:

Along the KKH, opposite to the Salmanabad and Ahmadabad, the slope is highly disturbed. A regional fault striking NE and dipping SE is running through this area. The fault and its splays crushed the rock outcrop. The area in front of Salmanabad is highly tectonized with a number of active slides **(DWG No: AFS-GE-319)**. The breccia consists of rock pieces with gaugic material **(Photo 4-61)**.

Photo 4-61 View of Active Slides in front of Salmanabad.

While the area in front of Ahmadabad also consists of brecciated rock but slopes are stable **(Photo 4-62)**. The drainage pattern is dendritic in higher elevation changes into parallel near the road which indicates that sheared rock is present up to higher elevations.

Photo 4-62 View of Stable Slide in front of Ahmadabad.

Photo 4-63 Panoramic View of Slope in front of Salmanabad and Ahmadabad Village

The rock at the slope in front of Ahmadbad along KKH is crushed, brecciated but there is no evidence of active tectonic forces in this section. Thin overburden ranging in thickness from 2 to 5 m underlain by sheared/ crushed rock, covers the slope. It suggests that the splay passing though this area is not active **(Photo 4-63)**. However, the topographic features, drainage pattern, left side slope of mountain terrain, and presence of brecciated rock in non-perennial nullah are clear cut indicator of fault system present in this area.

4.3.8 Upstream of Ganesh Bridge:

Coordinates:

N	4018284.00m
E	473257.772
El.	2211.23m a s l

Just upstream of the Ganesh Bridge, a large deposit of clayey silt is present at left bank of river underlain by thick RBGM material. It is observed that this material is under the influence of tectonic forces. The clayey silt beds have sheared zone striking at N72°E and dipping 88° SE **(Photo 4-64)**.

Photo 4-64 View of Shear Zone and Folding in Clayey Silt.

The clayey silt beds are folded across this shear zone. Associated with this, clayey silt beds have displaced along fracture plane with displacement of 12cm **(Photo 4-65)**. Beds of clayey silt are tilted up at an angle ranging from 6° to 20° in upstream direction. These features indicate that this area is under influence of active tectonic forces.

Photo 4-65 View of Micro Fault and Displacement of Blocks.

4.3.9 Near Kiln Upstream of Ganesh Bridge:

Coordinates

N	4018656.896m
E	471625.513m
El.	2185.0 m a s l

It is observing near Kiln that gravels, cobbles, and pebble in RBGM are tilted upward against the flow of Hunza River **(Photo 4-66)**. The inclination is 20° in RBGM and 18° in clayey silt beds.

Photo 4-66 Inclination in Gravel Bed near Kiln

Similarly, along KKH, tiltness in ABGM and clayey silt beds is observed ranging from 5° to 10° **(Photo 4-67).**

Photo 4-67 Inclination in ABGM and Clayey Silt Bed along KKH.

It is observed during site visit that some longitudinal joints are developed in morainic / slided mass, laying over the rock. It is evident that trend and sense of force is same as that of underlying rock **(Photo 4-68)**.

Photo 4-68 Development of Jointing in ABGM Underlain by Rock along KKH.

4.3.10 At Ganesh Bridge

The rock (Granotoide) with coarse to very coarse grained interbed marble is well exposed at left side along KKH. The rock is highly foliated and can split easily along this weak plane. Low amplitude folds with longitudinal joints are well developed. Some open joints intersecting with oblique joints might have caused the rock fall **(Photo 4.69)**.

Photo 4-69 Development of Longitudinal Joints in Rock along KKH.

The development of longitudinal joints in rock outcrop and falling of blocks show that some recent forces are operational in this area.

4.3.11 Just downstream of Ganesh Bridge:

Coordinates

N	4018200.432 m
E	470296.520 m
El.	2104.05 m a s l

At the confluence of Hispar River with Hunza River, there is thick deposit of RBGM present up to high elevations. The RBGM has subordinate sand beds. This recently deposited strata are quite disturbed. Many tectonic features have developed in this deposit including: -

- Inclination
- Folding
- Crenulation
- Folds with bulbus hing

Just upstream the confluence along Hispar River, thick RBGM is present along road. The material is under influence of intense deformation. The RBGM is tilted at an angle of 45° to 50° **(Photo 4-70)**. It is tilted upstream and extends up to higher elevations.

Photo 4-70 Inclination in RBGM at Left Bank of Hispar River.

The compressional forces responsible for deformation are associated with NE striking thrust faults passing near the area. Folding with bulbus hinge, box fold, recumbent fold are well exposed near the confluence **(Photo 4-71)**.

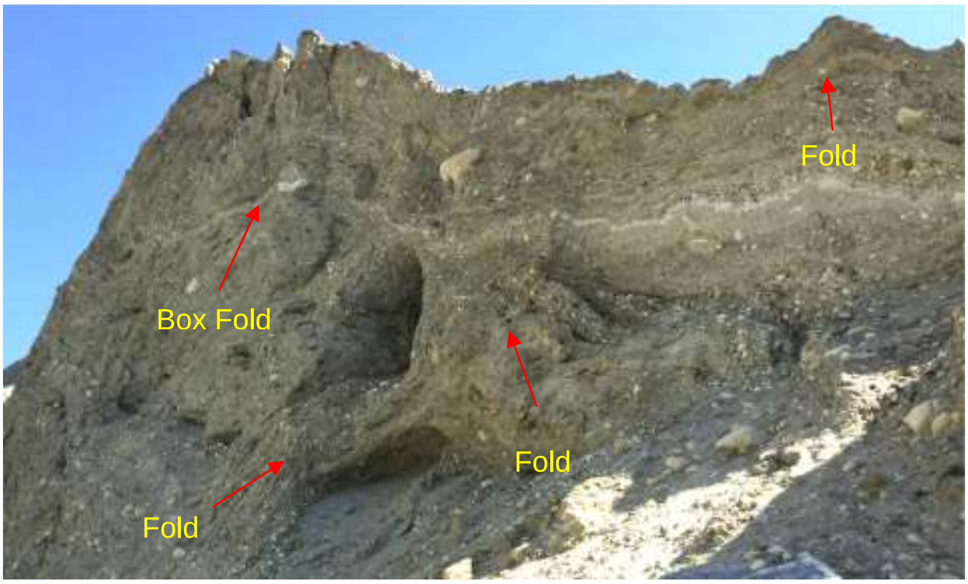

Photo 4-71 Folding in RBGM along Hispar River.

Due to intense compressional force, some beds are folded with inclined hinge. Both limbs are dipping in same direction **(Photo 4-72)**. The presence of folds in recent deposit indicates that, compressional force deformed this strata. The alignment of all folds is not uniform, indicates that multidirectional stress are applied in different episodes.

Photo 4-72 Inclined Isoclinal Fold In RBGM along Hispar River.

4.3.12 In Hispar Valley:

Coordinates

N	4017966.628m
E	470008.848m
El.	2107.24m a s l

Overall the geological conditions in Hispar Nullah are quite disturbed. The right side slope is mostly brecciated and consists of ABGM with RBGM. Gravel with sand beds is well exposed at the right side of Hispar Nullah are tilted up at an angle ranging from 22° to 30° **(Photo 4-73)**.

Photo 4-73 Inclination in Gravel Beds Tilted Upstream along Hispar River.

Major faults with their splays disturbed the area and extend further westward into Nagar valley. The whole valley up to Hoper Glacier is highly brecciated with some exposure of competent rocks.

Photo 4-74 Inclination in Gravel Bed Tilted Upstream along Hispar River.

It is clear in **(Photo 4-74)** that the sand layer is folded with inclined gravel beds with the formation of box fold, flat lower area with nearly straight limbs. These features were resulted from compressional forces associated with thrust fault.

About 3 km from confluence of Hispar and Hunza Rivers, the gravel beds are tilted at low angle ranging from 6° to 10°. The beds are tilted upstream, indicating upward movement of recent gravels **(Photo 4-75)**.

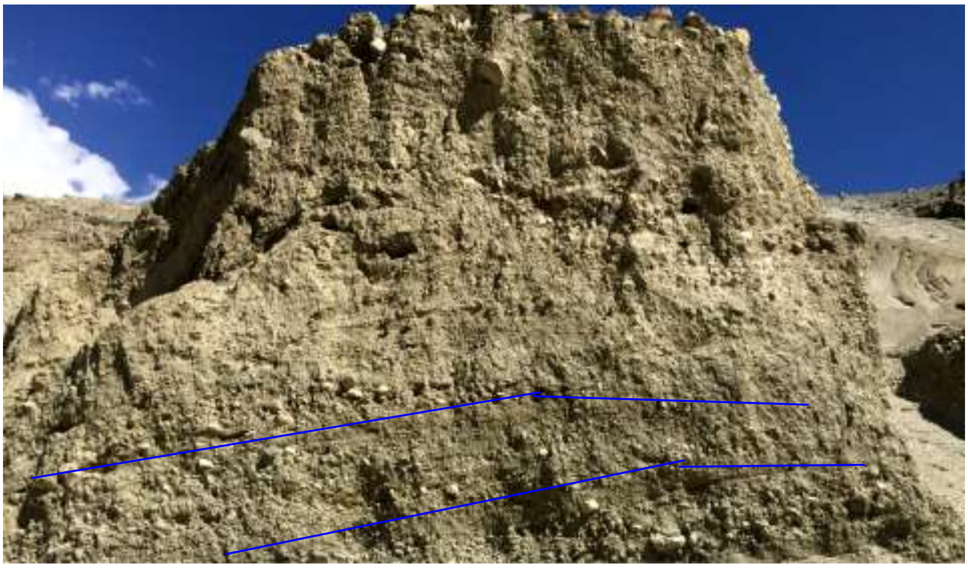

Photo 4-75 Inclination in Gravel Beds Tilted Upstream along Hispar River.

At Tukurkhai village, the fault breccia is exposed o both sides of a perennial nullah striking NE and dipping SE **(Photo 4-76)**.

Photo 4-76 Fault Breccia at Tukurkhai Village on Left Bank of Hispar River.

The rock is highly crushed and slopes are unstable. The nullah is developed along the extension of fault and well exposed along the road. All the terraces are developed upon the brecciated rock.

4.3.13 At Nagar Valley

The whole Nagar valley including Sumayar, Shahyar, and Hakuchar villages are situated on fault alignment **(DWG No: AFS-GE-320).** All the terraces were developed on fault breccia. Rocks are sheared and disturbed in this area **(Photo 4-77)**.

Photo 4-77 Fault Breccia near Hakuchar Village with Active Slides.

The slides are active, rolling down of material from crushed rock is quite common. It is present upto higher elevation and is responsible for the choking of Hunza River in the past. Due to development of lake, clayey silt was deposited and exposed along the both sides of river. The presence of active slides indicates that, fault is active in this area.

4.3.14 At Murtazabad - Shahyar Road

Coordinates:

N	4016299.113m
E	465418.47m
El.	2095m a s l

Just crossing the Murtazabad to Shahyar Bridge, a thick alluvial deposit consists of gravels, cobbles, pebbles interbedded with silty sand is exposed. This material moved upward against fault plane and formed fault bend fold **(Photo 4-78)**.

Photo 4-78 Inclination in Clayey Silt and Gravels.

The beds are tilted at an angle of 22° to 30°. Many micro faults in sand beds have been observed in hinge area of the fold. The ramp and flat geometry have NE strike with dip in SE direction. **(Photo 4-79)**.

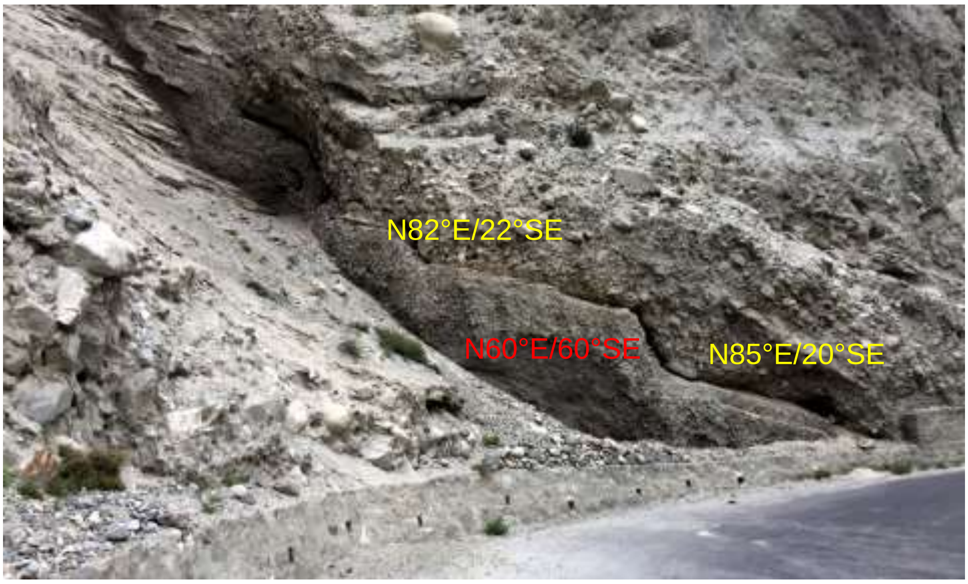

Photo 4-79 Ramp and Flat Geometry along Fault.

Some micro faults have been observed in this alluvium. Step faulting on micro level is well preserved in sandy material **(Photo 4-80)**. This alluvium is overlain by morainic material; same joint pattern is going to be developed in it. Some open joints ranging from 10cm to 150cm have been observed there. All these features indicate that the tectonic forces are active in this area.

Photo 4-80 Development of Micro Faults in Sand.

4.3.15 In Tashot Village

Coordinates:

N	4012830.531m
E	462157.244m
El.	2111.0ma s l

After crossing suspension bridge near Tashot Bridge, a thick deposit of RBGM and clayey silt is exposed along the road toward Phakhar village. Due to some recent activity, clayey silt is displaced and smeared along micro fault. Upward inclination of 6 °in recent RBGM has been found along the road **(Photo 4-81, 4-82)**.

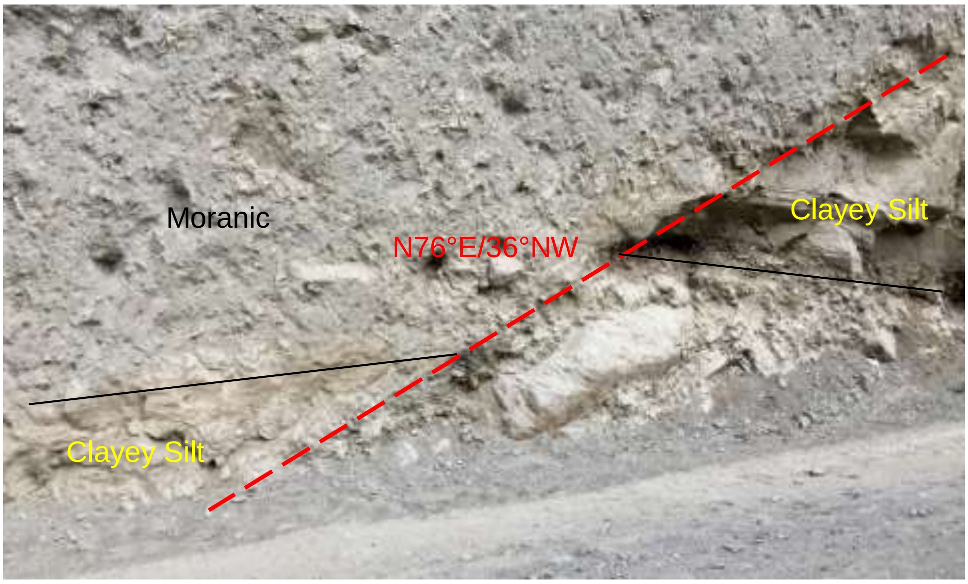

Photo 4-81 Development of Micro Faults in Clayey Silt.

Photo 4-82 Inclination in RBGM in Tashot Village along Road.

4.3.16 In Maichar Vllage:

Coordinates:

N	4012909.747m
E	461867.550m
El.	2098.0m a s l

At the left side slope of Hunza River, crushed rock with major constituents of gaugic material is exposed. The slopes are unstable due to active fault movement **(Photo 4-83)**. Well-developed garnets are present in granitic gneiss metamorphosed upto schistose grade.

Photo 4-83 Highly Crushed Rock in Maicher Village along Road.

Photo 4-84 Panoramic View of Crushed Rock and Drainage Pattern at Miachar Village.

A fault striking N45°E and Dipping 40°SE is running through Maichar village. Intersection of 3 to 4 faults, (coming from Central Hunza and Hassanabad Nullah), the rock is highly crushed and disturbed **(DWG No: AFS-GE-320).** Due to which, dendritic drainage pattern is well developed along the left side slope of the River. Fault breccia is well exposed along the road section.

Maichar village is developed on highly crushed rock with dominant gaugic material. The cultivated terraces are well developed on this material. Due to seepage of water and some tectonic movement along the faults, a large fracture seems to be opened along the slope, in back side of Maichar village. It is quite hazardous in the near future. The whole slope may become unstable and slide down.

5 CONCLUSIONS OF NEOTECTONICS STUDY

- The Project Area lies in KB, where Igneous, metamorphic and sedimentary rocks are exposed.
- It is a V-shaped valley originated by glacial activity, modified by river and controlled structurally by tectonic activity. The MKT and its splays at the Western side while Karakorum Fault and its splays at the Eastern side are the factor controlling the valley's morphology.
- The Project Area lies in the vicinity of active tectonic zone, responsible for the massive landslide at Attabad village. It chocked the Hunza River and creates about 25 km long lake up to Khyber village. After the excavation of spillway, the lake length reduces to 15 km.
- The area under study shows that the active tectonic forces are operational in this area; the sliding of huge rock mass is one of the major evidence of neo-tectonic activity.
- During the current study about 40 km upstream and 50 km downstream area have been investigated. There are many deformational features observed in the recent deposit. Many evidences of chocking of Hunza River have been found in deposited clayey silt at number of locations.
- During site visit many deformation phases have been observed in the recent deposits including, faulting, folding (fault bend fold, chevron fold, ramp and flat geometry), jointing, tiltness in sand and gravels, step faulting, cross bedding etc., throughout the stretch. These structural features are associated with different thrust fault systems under compressional regime.
- The whole area suffers under tectonic forces that might have contributed some seismic events in this area. During the study fault geometry, nature of fault, and slope disturbed due to these faults have been studied to incorporate in Seismic Hazard Analysis Report.

6 SEISMIC HAZARD ASSESSMENT

6.1 INTRODUCTION

Hydro Planning Organization (HPO), Pakistan Water and Power Development Authority (WAPDA) have undertaken the Feasibility Study of ALHPP in GB.

The proposed Project is located on Hunza River about 20 km upstream of Aliabad village about 130 km from Gilgit and about 750 km from Islamabad. Project Area is under the administrative control of GB. Hunza River is one of tributaries of the Indus River. The location coordinates of newly proposed inlet portal of diversion tunnel has been used as tentative reference coordinates for seismic hazard analysis of the Project and the coordinates are given below:

Latitude	36.313 N
Longitude	74.861 E

As the earthquakes hazard to water retaining structures is very important consideration in the design of civil structures, it requires careful analysis for selecting seismic design parameters for water retaining structures. The goal of the earthquakes-resistant design is to produce a structure that can withstand a certain level of shaking without excessive damages to the water retaining structures. Thus, the specification of design ground motion parameters is one of the most important difficult and most important problems in geotechnical earthquake engineering.

The Project Area lies in a unique geo-environment where all the typical hazards associated with mountainous areas exists including twin geo-hazards of earthquakes and landslides in addition to the possible danger of accidental and irregular melting of glacial waters resulting in huge sediments-loaded flooding potentials. Keeping all the triggering factors in view, care has been taken while selecting seismic design parameters for the updating Feasibility Study of the 54 MW ALHPP located on Hunza River. A composite map showing the location of the Project Area along with important physical features of the catchment areas and the area selected for seismicity analysis (Catalogue) is presented as Figure 6-1.

The Project Area lies in KB to the north of the MKT. Consequently, the MKT is the most prominent tectonic feature close to ALHPP, located at a distance of 32 km from the Project Site. Geological Map of Northern Pakistan and re-created Geological Map of Hunza Area were used in the softwares for seismic hazard analysis and these maps are presented as Figure 6-2.

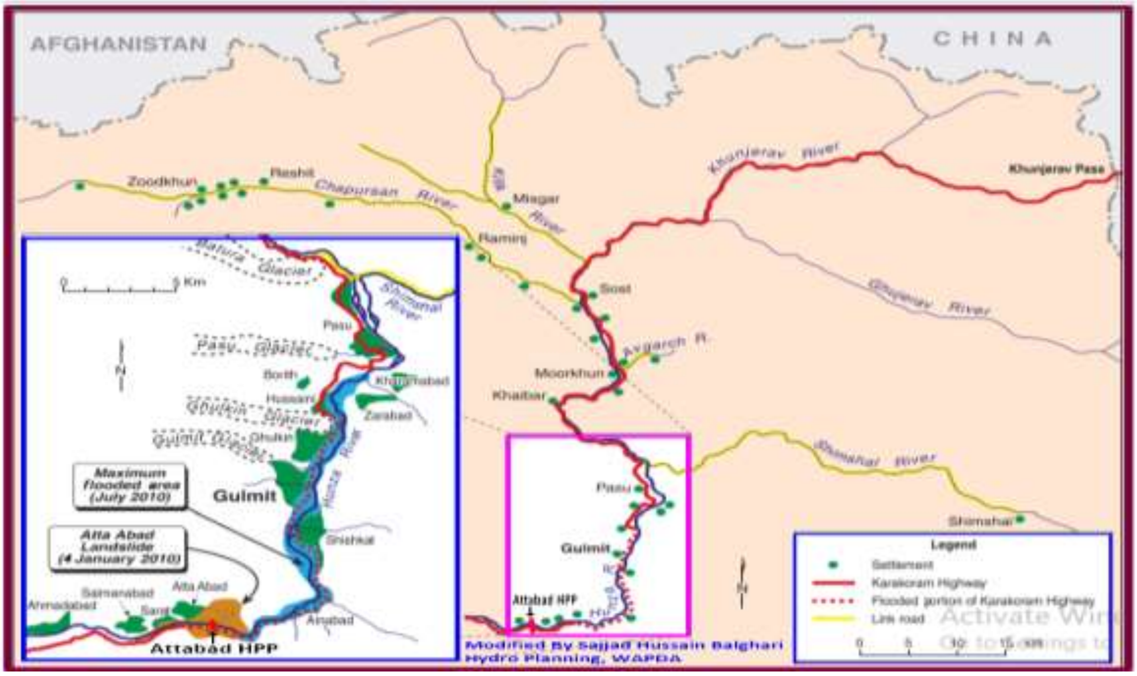

Figure 6-1 Composite Map Showing Location of ALHPP Site.

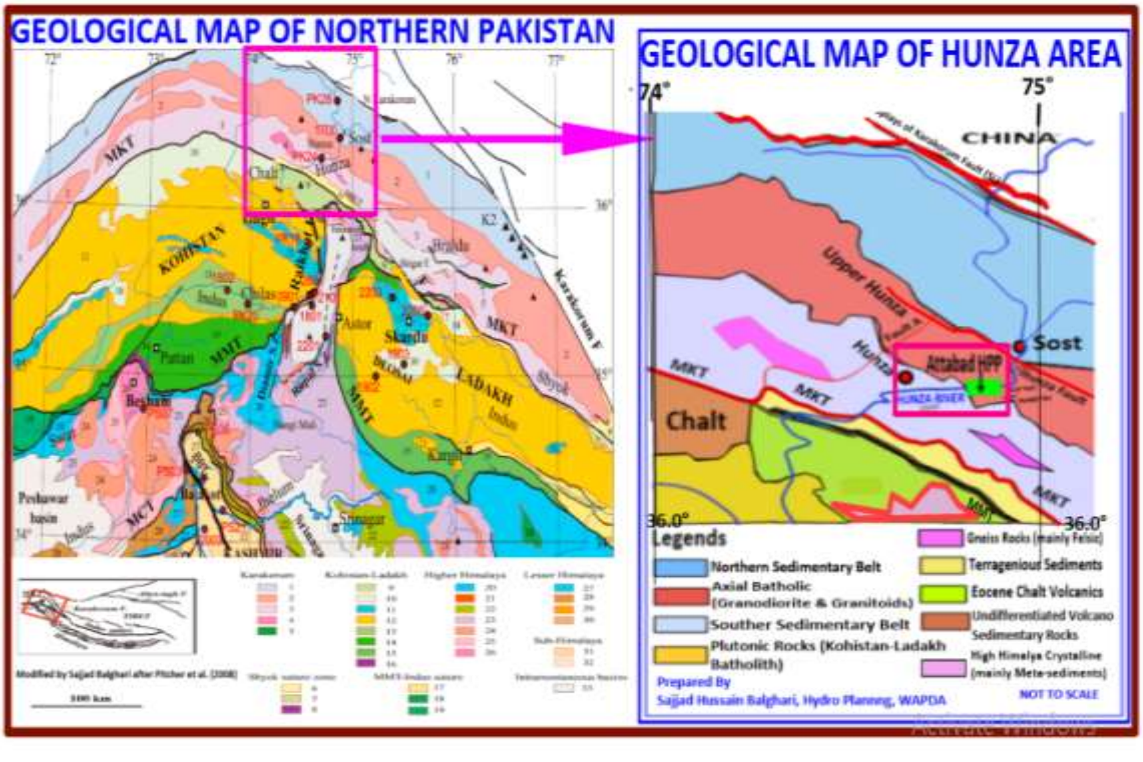

Figure 6-2 Geological Map of Northern Pakistan (Pecher et al. 2008) & Geological Map of Hunza.

Explanation to Legends (Left Map) i.e. Geological map of the Northern Pakistan modified by HPO, WAPDA after Pêcher et al. [2008]. Main tectonic boundaries: MKT, MMT, (Indus Suture Zone); STD, South Tibetan Detachment; MCT MBT; MFT, Main Frontal Thrust; BBT, Balakot-Bagh Thrust. Geological units at ALHPP are underlined: 1. Northern Sedimentary belt; <u>2, Axial Batholith, Granodiorites and other Granitoids; 3, Southern metamorphic belt; 4, Felsic gneiss;</u> 5, greenstone complex, Paleozoic (Masherbrum complex). Unit B Shyok Suture Zone: reactivated along the MKT, 6, Predominantly terrigeneous formation; 7, Melange zone (volcanic); 8, Ultramafics (Shyok and Dobani-Dassu lineament). Unit C Kohistan: 9, Eocene Chalt Volcanics, Turmik volcanosediments; 10, Undifferentiated volcanosedimentary group; 11, Metasediments; 12, Plutonic rocks (Kohistan and Ladakh batholith); 13, Gabbronorites (Chilas Complex); 14, Southern amphibolites (Kohistan); 15, Dras volcanosedimentary group (Ladakh); 16, Mantle ultrabasites (Jijal complex). Unit D MMT-Indus suture zone: 17, Indus Molasses; 18, Spontang ophiolites; 19, Imbricate thrust units, with blue schists. Unit E Higher Himalaya: 20, Neotethyan Sedimentary Group (Permian-Eocene); 21, Tertiary leucogranites (Ladakh and Nanga Parbat); 22, Panjal Traps (Permian); 23, High Himalaya Crystalline (mainly metasediments, Late Proterozoic to early Paleozoic); 24, Paleozoic intrusives (Swat and Manserah Granite, Kohistan; Bhazum and Kade Granite, Ladakh); 25, Basement gneiss (dominantly Early Proterozoic orthogneiss); 26, Besham Metaigneous. Unit F Lesser Himalaya: 27, Paleozoic-Eocene cover; 28, Upper nappe, dominantly Early Proterozoic metasediments (Abbottabad, Kishtwar); 29, Lower nappe, dominantly Late Proterozoic-Paleozoic metasediments (Kishtwar, Kashmir); 30, Salt Ranges (Late Proterozoic-Eocene Indian cover). Unit G sub-Himalaya: 31, Murree and Subatu Formations (Eocene to Miocene); 32, Siwaliks (middle Miocene to Quaternary); 33, Peshawar and Srinagar intramountaneous basins (Quaternary). For seismic hazard analysis, studies of regional geological and tectonic information were collected from the available literature with requisite updates of maps wherever required.

6.2 TECTONIC SETTING

6.2.1 General

From a seismic hazard point of view, the contact zones between adjacent tectonic plates are considered to be the most vulnerable parts to generate earthquakes of varying scales and magnitudes

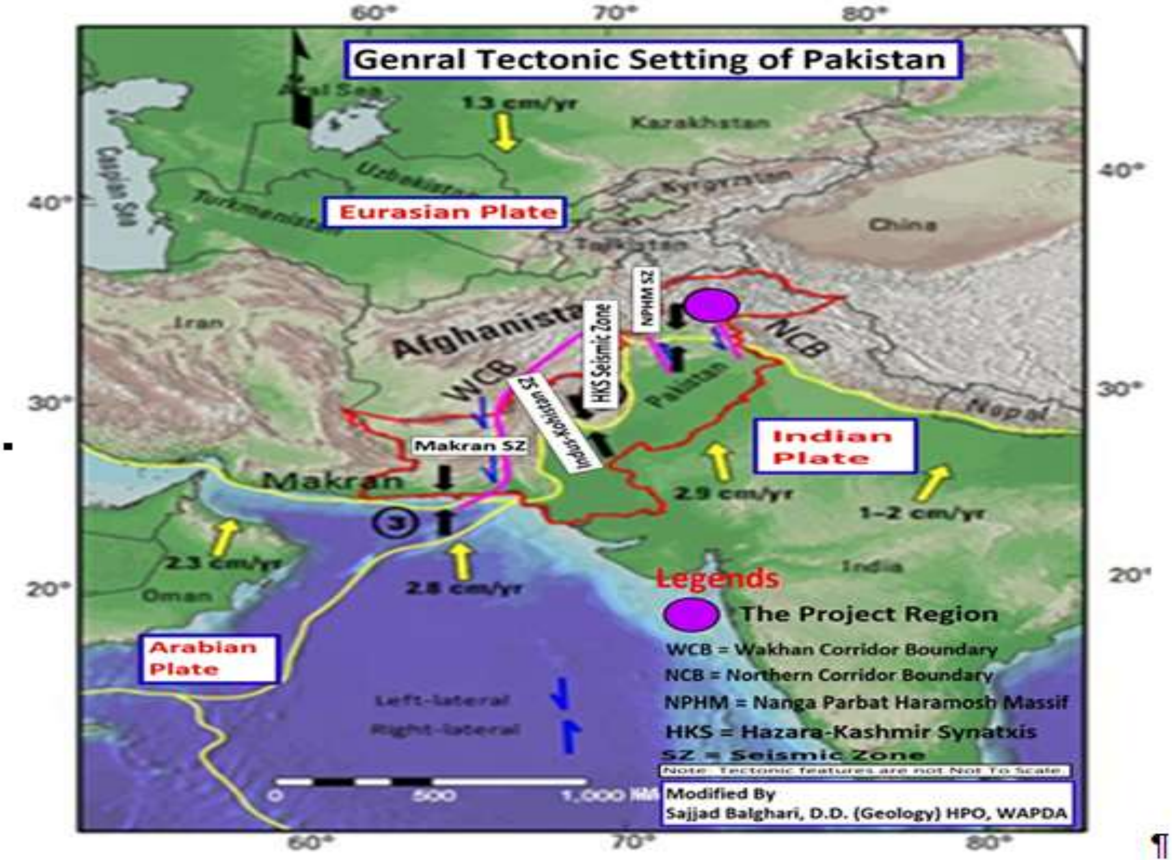

Figure 6-3 General Tectonic Setting of Pakistan.

ALHPP is in the proximity of the collision zone between the north moving Indian Plate and the Eurasian Plate which is over-riding the Indian Plate at a rate of 3 to 4 cm/year as shown in Figure 6-3.

6.3 Regional and Local Tectonic Features

6.3.1 General

The collision tectonics has resulted in the development of a series of geologic faults and the occurrence of frequent earthquakes in Northern Pakistan. The subduction zone of the Indian Plate beneath the Eurasian Plate has resulted in folding and thrusting of the upper crustal layers near the collisional boundary. The distribution of the modern tectonic stress field near Western Himalayan syntaxis is controlled by the collision zone of the Indian Plate and the Eurasian Plate. Due to north and north-east movement of the Indian Plate (Figure 3) in the Northern Pakistan and Kashmir Areas of Pakistan and India, the focal mechanism solution for various earthquakes reflects that the area is under principal compressive stress in the direction of NE-SW and most of the seismogenic faults are thrust fault. The thrusting has been depicted from north to south in the shape of MKT, MMT, MCT, MBT and SRT. Locations of regional and local tectonic features are shown in Figures 6-4 to 6-9.

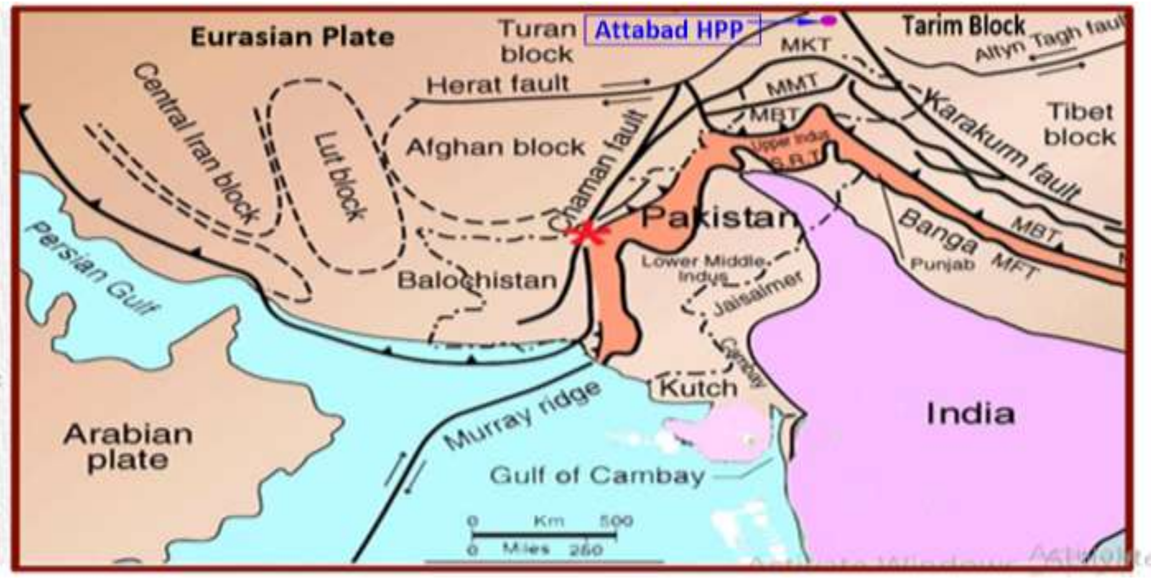

Figure 6-4 Major Tectonic Faults of Pakistan, Pink Circle Shows the Project Area.

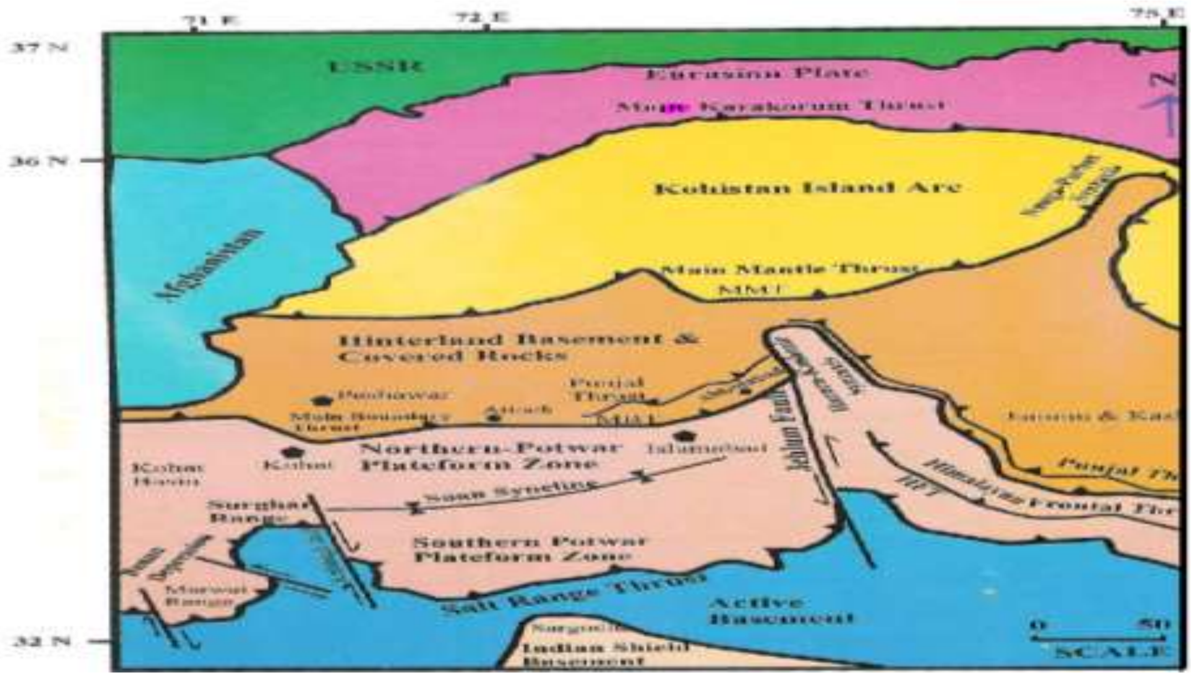

Figure 6-5Tectonic Map of Northwestern Himalayas (Northern Pakistan)
(Reference: Building Code of Pakistan)

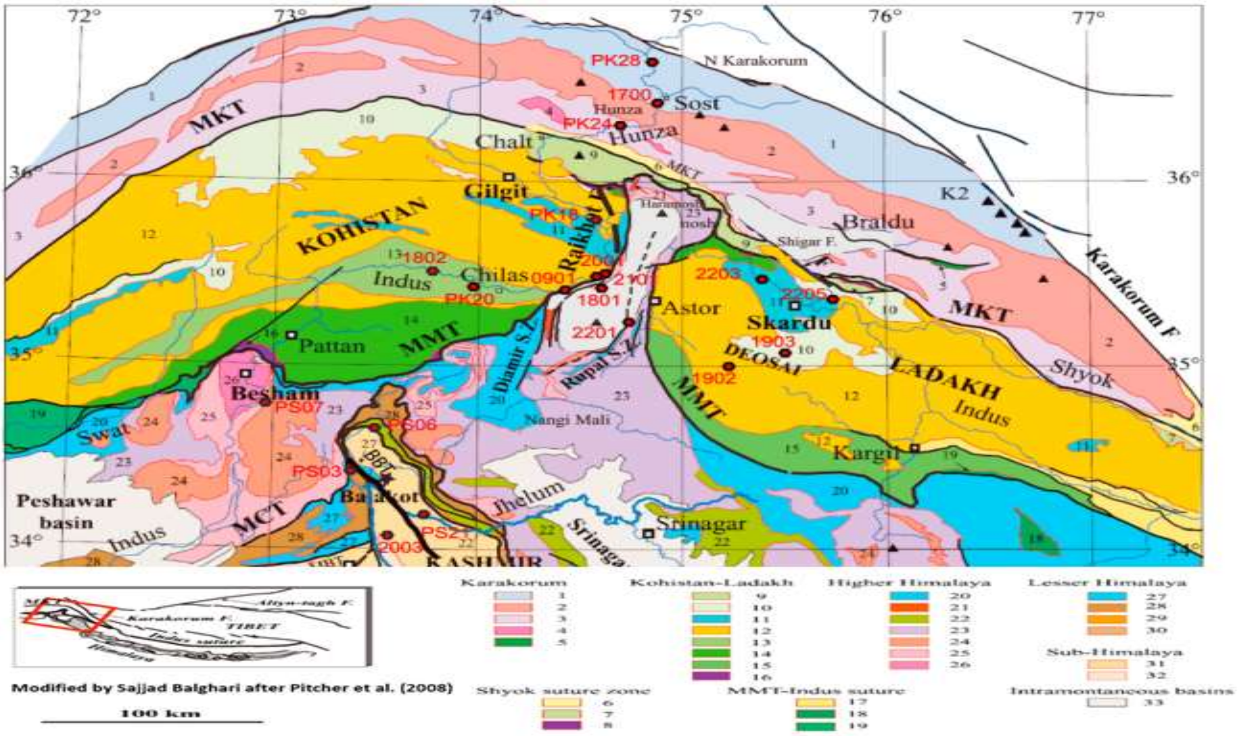

Figure 6-6 Geological Map of Northern Pakistan.

The major faults of region include, from North to South, the Main Karakoram Thrust (MKT), Main Mantle Thrust (MMT), Main Central Thrust (MCT), Panjal Thrust (PT), Nathia Gali Thrust (NGT), Main Boundary Thrust (MBT), Kashmir Boundary Thrust (KBT) / Himalayan Frontal Thrust (HFT) and Salt Range Thrust (SRT) and these faults are shown in Figure 6 to 8. The general trend of these faults is predominantly East-West with change in trend at places due to syntaxial bends.

The brief descriptions of these major faults are as follows: -

6.3.2 HUNZA FAULT (HF)

The upper HF is considered as the northern limit of Main KTF (Pitcher et al. 2008 and Desio et al. 1979) and it is present at the Project Site at a distance of about 1.4 km from the proposed intake / diversion tunnel of ALHPP. It is thrust type fault. It is considered as a major local fault to which is associated with many small local faults in the Project Area.

Although geologically the Project Area is characterized by many local faults and tectonically very disturbed area but the seismic data show that these faults are dormant due to low seismic activity with seismicity class of moderate seismicity at the site as depicted from the analysis of seismic data of the past 200 years.

6.3.3 MAIN KARAKORAM THRUST (MKT)

The MKT is a low angle mega-shear thrust fault with strike slip components as segmented regime at places, which passes through Chalt (near Hunza) on eastern side and extended on western side through Ishkuman and Yasin valleys into Baltistan Area in Hasupa Shigar valley, Machelu in Shyok valley and Shishi valley. In Chitral Area, it encircles the Island Arc Zone on the northern side. Its general trend swings between E and E-NE and dips towards the north at low to medium angle. It is 32 km away from ALHPP towards south. Some segments of this 700 km long thrust fault is seismically active.

6.3.4 MAIN MANTLE THRUST (MMT)

The MKT is a low angle mega-shear thrust fault with strike slip components as segmented regime at places, which passes through Chalt (near Hunza) on eastern side and extended on western side through Ishkuman and Yasin valleys into Baltistan area in Hasupa Shigar valley, Machelu in Shyok and and Shishi valleys. In Chitral area, it encircles the Island Arc Zone on the northern side. Its general trend swings between E and E-NE and dips towards the north at low to medium angle. It is 32 km away from ALHPP towards south. Some segments of this 700 km-long thrust fault is seismically active.

6.3.5 MAIN CENTRAL THRUST (MCT)

It is E-W trending fault separating Higher Himalayas in north and Lesser Himalayas in south, exposed in Upper Kaghan valley, Neelum valley, Northern Hazara, Swat and Dir (chaudhary et. al, 1994). Generally, it is a ductile shear zone along which a distinct break in metamorphism is observed along this thrust, toward North, metamorphism of upper amphibolites to eclogite facies took place while to the south, green schist facies are present. It is seismically active fault.

6.3.6 PANJAL THRUST (PT)

PT is nearly NW–SE trending fault on Eastern side, bending at 180° around Hazara Kashmir Syntaxis (HKS) and have NE-SW trend on Western side, separating Lesser Himalayan Igneous and Metamorphic Zone in the north from Sedimentary Zone in the south. It traces Eastward in Kashmir basin, at the foot hill of Pir-Panjal ranges through India and extends westward through Mansehra, Attock, Nowshera, Peshawar and Afghanistan. It is seismically active fault.

6.3.7 NATHIA GALI THRUST (NGT)

It is nearly NE-SW trending thrust originates from Western side of Hazara Kashmir Syntaxis (HKS) extends westward through Hazara area (well exposed in Jabri and Khanpur Area) and Kala Chitta Ranges to Afghanistan. It is low angle fault along which Tertiary rocks are in contact with Precambrian rocks (slates). It is seismically active fault.

6.3.8 MAIN BOUNDARY THRUST (MBT)

The MBT is the most significant and active tectonic feature of regional extent separating Lesser Himalayas in the north from Sub Himalayas in the south. It runs along the Himalayan Arc for about 2800 km from the Asam in the east to Kashmir and Parachinar in the west. MBT along with other associated thrusts forms a sharp conspicuous Hazara-Kashmir Syntaxis(HKS). This syntaxial bend is the most dominant tectonic feature of the area as all local major fault systems and geologic structures follow its trend. Near its surface trace the MBT dips Northward at a steep angle, which becomes sub horizontal with depth. The Project Area is located to the North of this fault. It is also seismically active fault.

6.3.9 KASHMIR BOUNDARY THRUST / HIMALAYAN FRONTAL THRUST (KBT/HFT)

It is nearly NW-SE trending fault coming from India which become nearly NW and SE trending thrust near Kotli, joins HKS, northward with other faults in the Western epical portion. Toward south passing through Garhi Habib Ullah, Muzaffarabad, Domel and Kotli, runs eastward to India. A devastating earthquake of October 08, 2005 having magnitude 7.6 on scale is associated with rupture along this fault having epicenter, about 10 km upstream of Muzaffarabad in Gohri-da-Katha (right tributary of Neelum River).

6.3.10 SALT RANGE THRUST (SRT)

It is seismically active fault along which Precambrian rock e.g. SRF is exposed. It separates the Sub Himalayas from Punjab Plains. It is dissected Westward by Kalabagh Fault, a right lateral strike slip fault and eastward by Jhelum Fault, a left lateral strike slip fault.

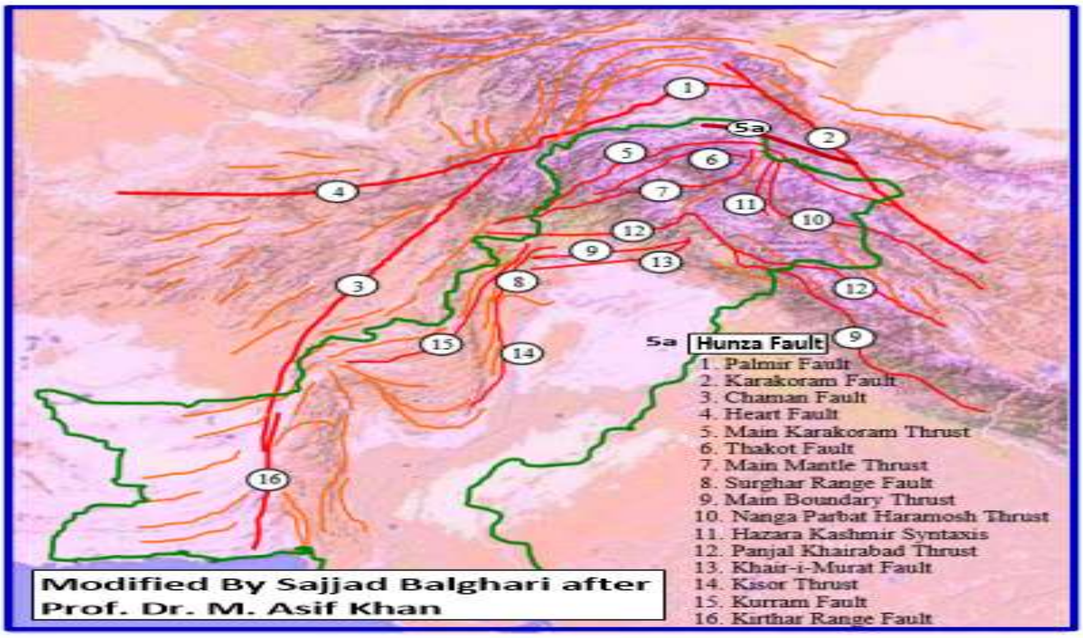

Figure 6 -7 Faults Map of Northern Pakistan Marked on Satellite Map (Modified after Dr. Asif Khan)

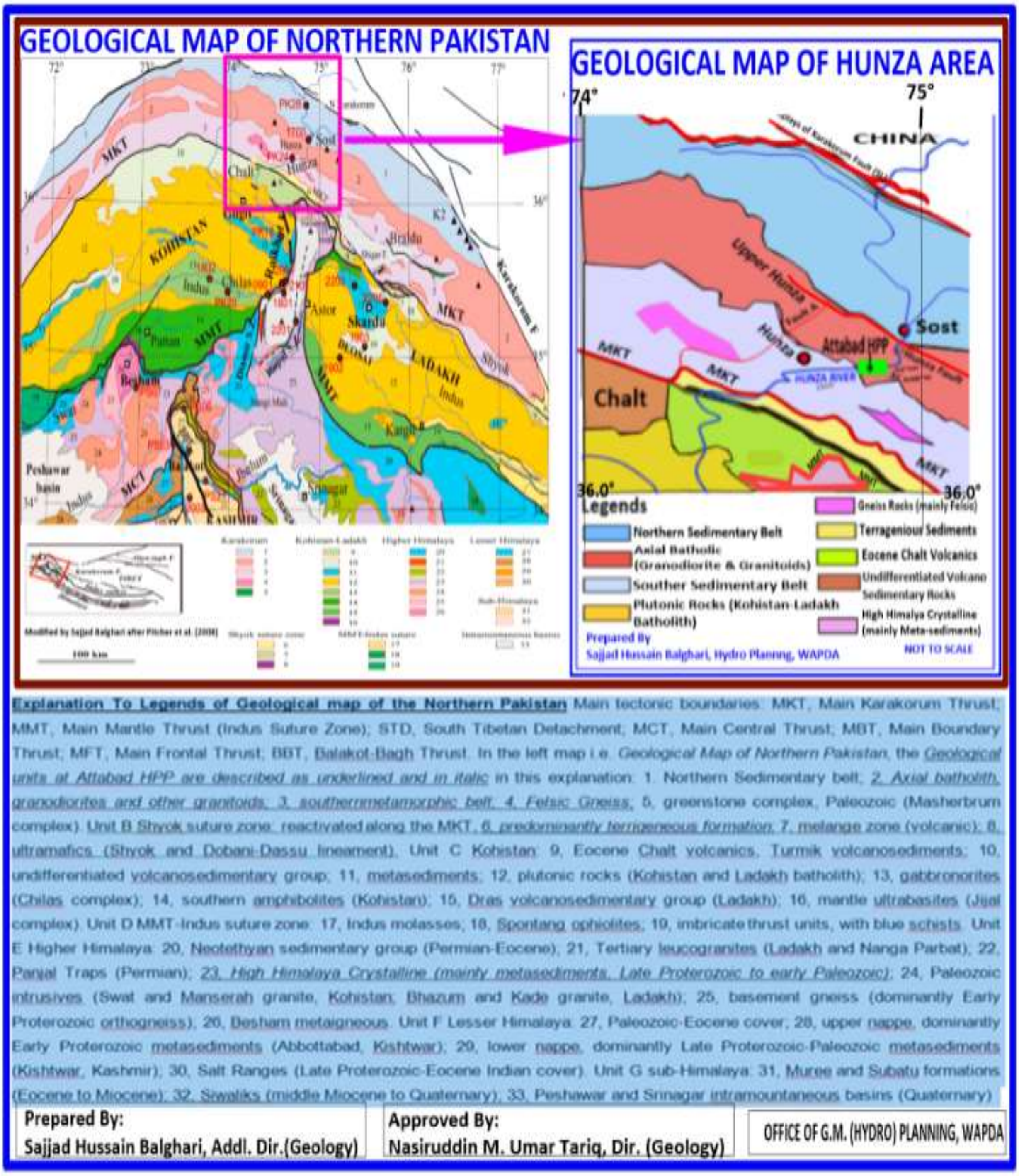

Figure 6-8 Geological Map of Northern Pakistan and Geological Map of Hunza Area

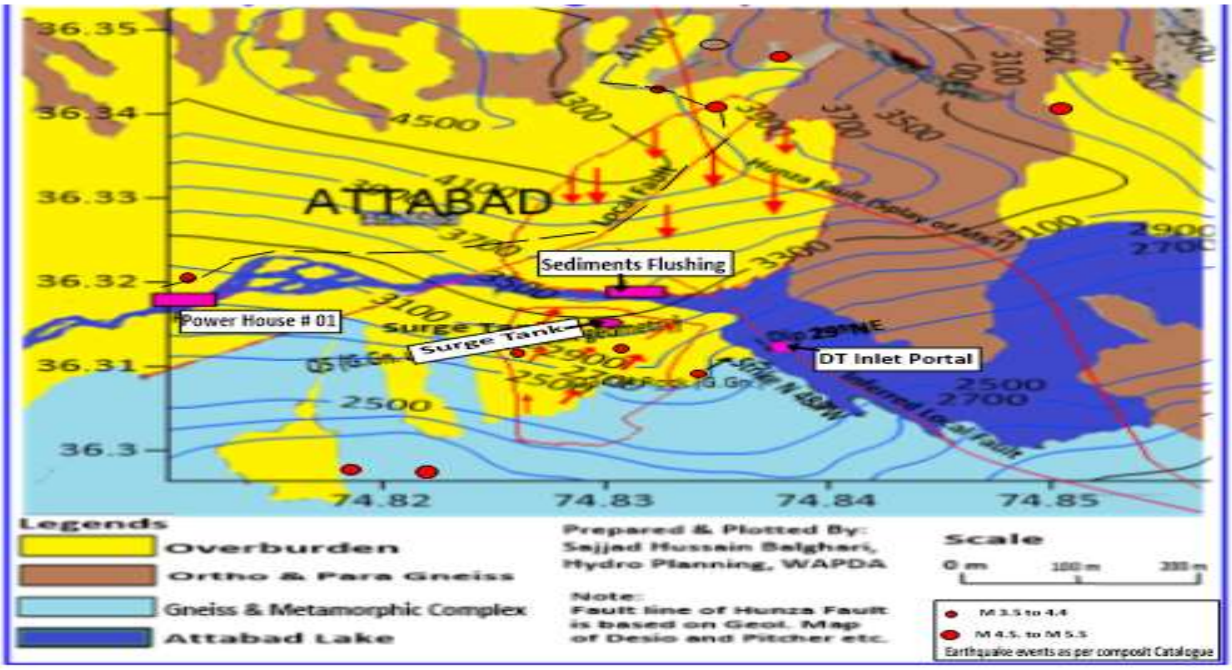

Figure 6-9 Composite Map Showing Site Geology and Seismicity with Preliminary Project Layout.

6.4 SEISMICITY OF PROJECT AREA

6.4.1 General

The Project Area lies in the region of Northern Pakistan which has high frequency of earthquakes especially in the Himalayan Orogenic Belt. This belt represents the contact between Indo-Pak and Eurasian Plates, which has always been the source of moderate to large earthquakes including Kangra (1905), Bihar-Nepal (1934), Assam (1897) and 2005 Kashmir earthquakes with significance consequences. The presence of some of the active faults like MKT, MMT, Raikot Fault, Riwat Fault, Panjal Khairabad Fault, Jhelum Fault and MBT etc. make the Northern Pakistan region tectonically very active. However, in this area of dominantly collisional tectonics, a large number of focal mechanism solutions indicate thrust faulting with some strike-slip faulting as segmented faulting system (Fitch, 1970; Rastogi, 1974; Armbruster et al., 1978; Verma et al., 1980; Verma and ChandraSekhar, 1986; Molnar and Lyon Caen, 1989; Pivnik and Sercombe, 1993, MonaLisa et al., 1997, MonaLisa et al., 2003 and Khwaja et al., 2003). A kinematic change from compression to transgression is believed to be taking place at places (Pivnik and Sercombe, 1993). Both historical / non instrumental and instrumental data exist in the area. The instrumentally recorded earthquake data are available only since 1904. Seismic hazard analysis involving the quantitative estimation of ground shaking hazards is of great importance for hydropower projects proposed in seismically active zones. The region selected for acquiring tele-seismic catalogues is shown as brown rectangle in the satellite map given as Figure 6-10.

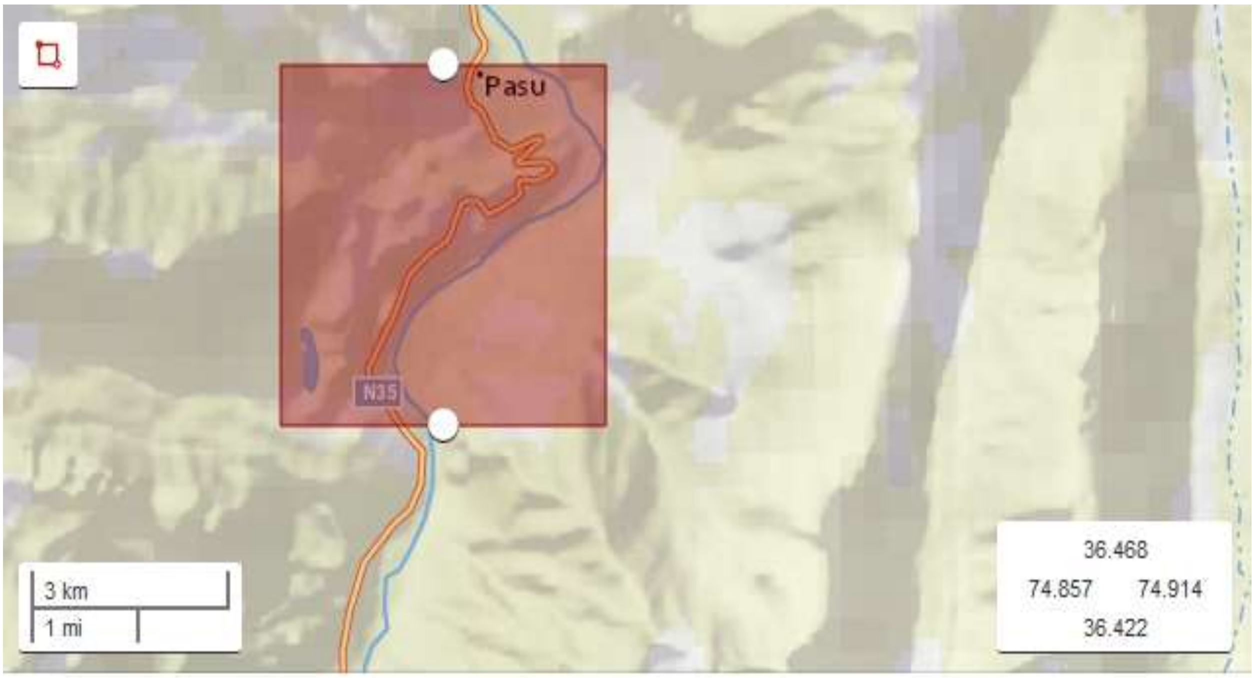

Figure 6-10 Region Selected for Acquiring Tele-seismic Earthquakes Catalogue

6.4.2 STUDY AND ANALYSIS OF EARTHQUAKES DATA

Study and analysis of the earthquake record involved several activities including;

a. Investigation of the historical seismicity
b. Acquiring earthquake catalogues both international and national catalogues including WAPDA earthquakes catalogue
c. Examination of instrumentally recorded earthquake record.
d. Statistical analysis of catalogue data and determination of standard deviation.
e. Determination of input values such as upper maximum magnitudes, minimum magnitudes, b-values, beta, lamda, rupture etc. for each seismic source.
f. Interpretative description of the new scenario after Kashmir Earthquake of October 8, 2005
g. Analysis of the earthquake records (both historical and instrumental data)
h. Preparation of seismicity maps.
i. Presentation of interpreted results including focal mechanisms etc.

Both historical and instrumetal records of earthquakes were acquired from international and national agencies for compilation of updated composite catalogue.

For seismic hazard assessment, the guidelines provided by International Commission on Large Dam (ICOLD, Bulletin 148, 2016) for selecting seismic parameters for large dams has been followed. For preparation of input maps in acceptable formats (i.e. shape files), ArcGIS and Surfer softwares were used.

For performing seismic hazard analysis, the latest version of R-CRISIS V.20.1.1 and Ez-Frisk Software were used with a purpose of comparison of results and cross checking for validation testing.

6.4.3 Historical (Pre-Instrumental) Seismicity

The historical pre-instrument earthquake data for GB has been collected from the literatures and non-instrumental earthquakes catalogues such as catalogues of Oldham, 1893, Heukroth and Karim, 1970, Ambraseys et al. 1975 and Quittmeyer and Jacob, 1979 and other national and international sources as shown in Figure 6-11.

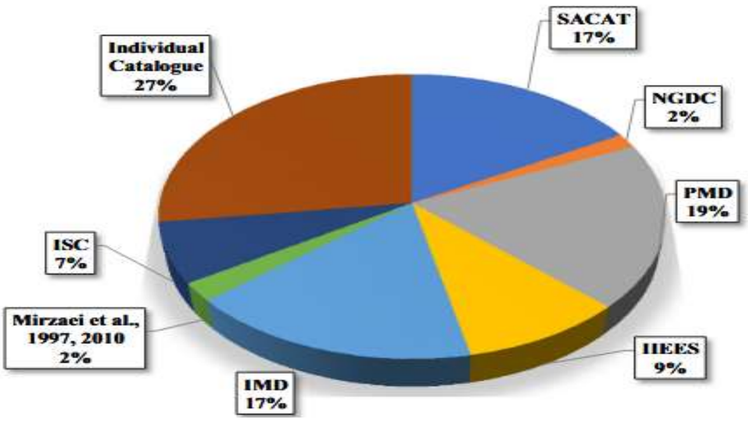

Figure 6-11 Pie Chart of Historical Sources for Compilation of Composite Earthquake Catalogue.

6.4.4 Analysis of Historical (Pre-Instrumental) Seismicity

The analysis of historical earthquake data reflects that Northern Pakistan as a whole has remained a house of prominent earthquakes but the events are sparse at the Project site (please refer to Figure 5). Taxila earthquake (25 A.D.) event is probably the most conspicuous one that had changed style of building-construction after the devastating event.

However, the catalogue of historical earthquakes for GB Region is rather sparse, mainly due to remoteness of this hilly terrain as well as non-availability of local seismic networks in the area. Since the 1700's, the historical earthquake data for GB are few and mainly concentrated on the centres of colonial administration. However, the situation is now improving as WAPDA is extending its seismic stations with the passage of time.

In the present analysis of historical earthquakes around ALHPP, the analysis of historical earthquake events was performed in Ez-Frisk Software using the historical earthquakes database and the analyzed results is presented as Figure 6-12.

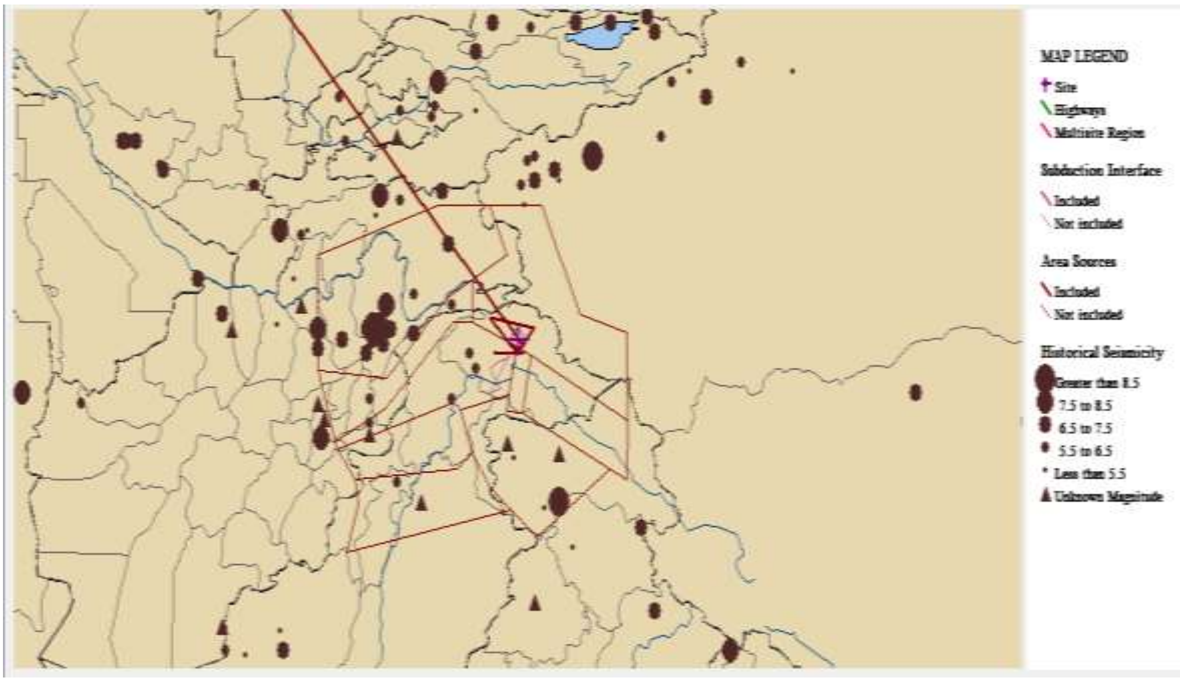

Figure 6-12 Historical Earthquakes Map around ALHPP and Adjoining Areas Analyzed in Ez-Frisk Software.

6.4.5 Instrumental Seismicity

The instrumental recording of earthquakes started in 1904 but very few seismic stations were established in the South Asian Region until the 1960's. However, with the installation of high quality seismographs under the World Wide Standard Seismograph Network (WWSSN) established by the U.S. Coast and Geodetic Survey in 1960, the quality of earthquake recording in this Region improved and resulted in a better understanding of the seismicity of Pakistan as well.

In Pakistan and most other parts of the World, the seismic record is too short and incomplete to develop a complete sample that is truly representative of the spatial and temporal distribution of earthquake shocks over a large period. Nevertheless, all the available information has been gathered for the period covering the last century, which was used to develop a satisfactory and safe assessment of seismic hazard for the Project.

For this study, the instrumental record of earthquakes within a radial distance of about 200-km of the Project was searched and acquired from both international and national sources as shown in Figure 6-13.

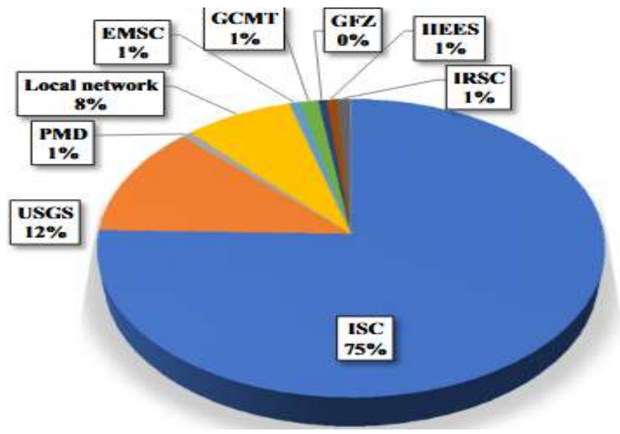

Figure 6 -13 Pie Chart of Instrumental Sources Contributing to the Compilation of Composite Earthquake Catalogue

6.4.6 Analysis of Instrumental Seismicity

The spatial and temporal distribution of the earthquakes events with magnitudes of the past 100 years at and around the ALHPP Site is shown as Figure - 14 &15. The seismicity within a 200 km radius of the Project Site were analyzed using the composite catalogue and the results are presented in Figures 6-12 to 6-18**.**

Hunza Fault exists within the Project Area at a distance of 2.4 km from weir site whereas the MKT is the second nearest fault, located at a distance 32 km from Project Site and the last limit of the MMT is at a distance of 71.69 km away from the Project Site (please refer to Figure - 2).

According to the field geologists who carried out geological mapping at the site, there are many micro faults and neotectonic features at site which shows that the Project Area is tectonically very disturbed. However, the analysis of the seismicity data (both historical and instrumental) shows that earthquake events are not concentrated in the Project Area. (please refer to Figures 6-7 to 6-12**).** The comparison and correlation of seismicity analysis with tectonic and geologic data lead to the understanding that the geologic deformations including micro faults may be viewed as deformations tectonically associated with MKT which triggered its associated splays and surrounding tectono-geologic environment in the past.

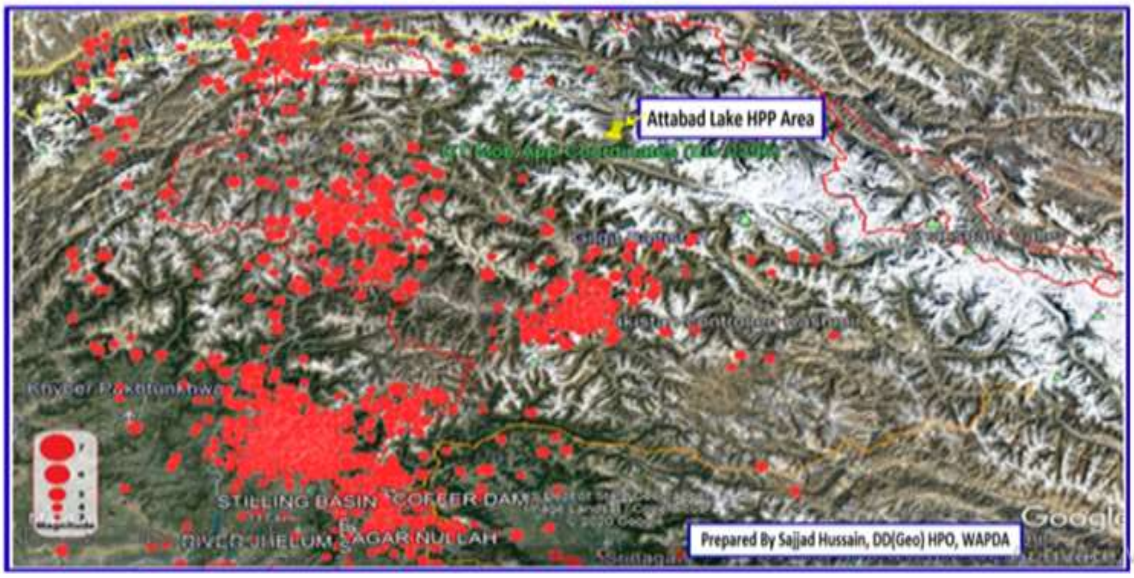

Figure 6 14 Temporal Distribution of the Earthquakes Events with Magnitudes of the Past 100 Years, Pink Rectangle Shows ALHPP Site.

As can be seen from instrumentally recorded earthquake events of the past 100 years data (Figure 6-14) and historical earthquakes around the Project Site (Figure 6-12) that there is very low concentration of earthquake events around the Project Site. However, if local micro-seismic network is installed at the Project Area at belated stages, more coverage and representation of the earthquakes events may result at belated stages. Analysis of the composite earthquakes catalogue data shows that the nearest magnitude at the Project Site is M4.7 and the maximum magnitude nearest to the site is M5.2. as shown in figure 6-15

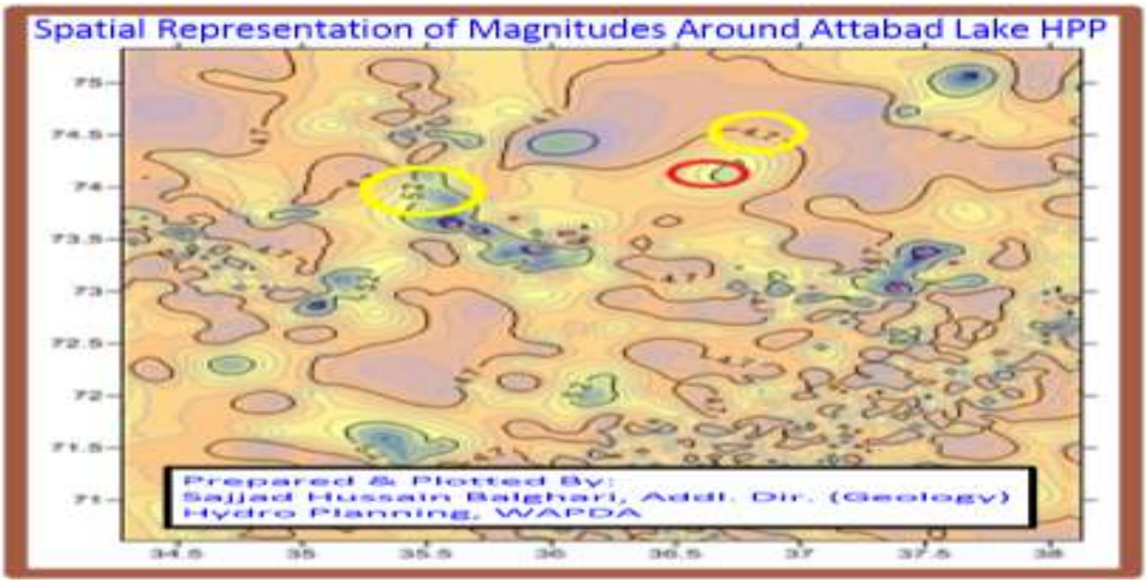

Figure 6-15 Distribution of Earthquake Magnitudes of the Project Area (Red Circle Shows the Project Area).

A composite map showing seismic basins of Pakistan and Hunza Area and Seismic Zonation map of Building Code of Pakistan (2007) covering historical earthquakes data is presented as

Figure 6-16 which shows that the maximum magnitude of the Project Region (Hunza-Nagar) is M 6.1.

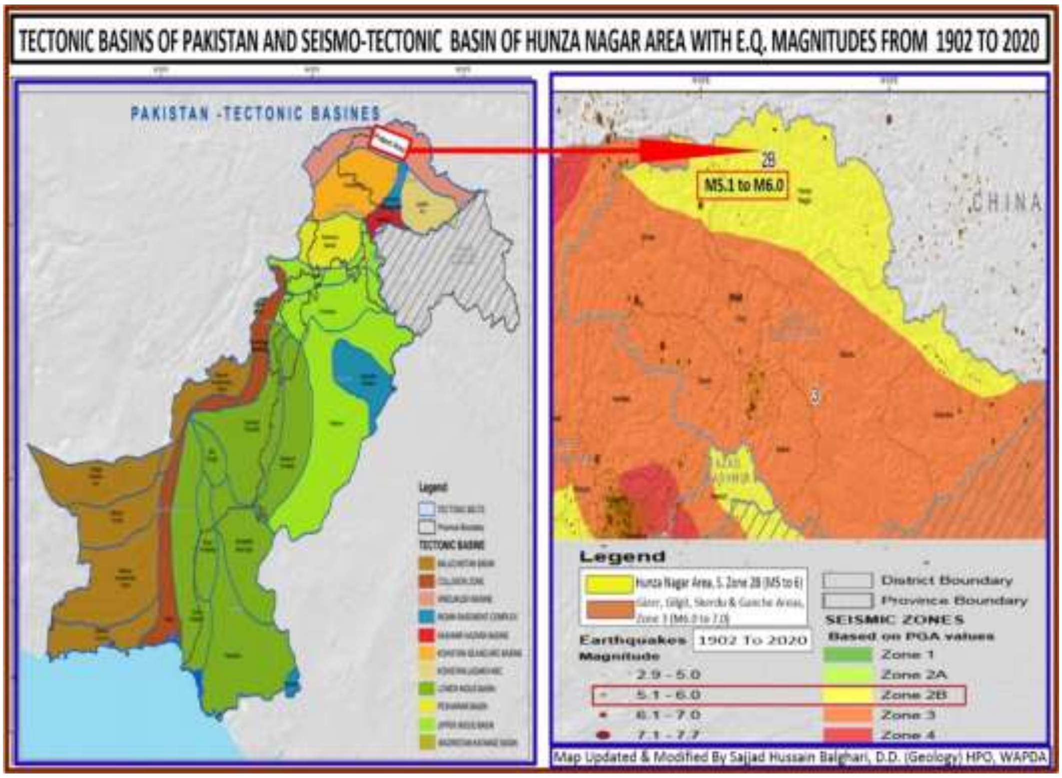

Figure 6-16 Composite Map Showing Seismic Basins of Pakistan and Hunza Area and Modified Seismic Zonation Map (Revised Building Code of Pakistan, 2007)

However, in the present seismic hazard analysis, the maximum magnitudes for the near-field seismic sources for the Project Site has been conservatively assigned higher in seismic hazard assessment for the Project keeping the safety factors in view as well as perceiving the tectonic scenario of Hunza Fault as a splay of MKT.

Earthquakes depth map developed from composite earthquakes catalogue data at and around the ALHPP Area is presented as Figure 6-17

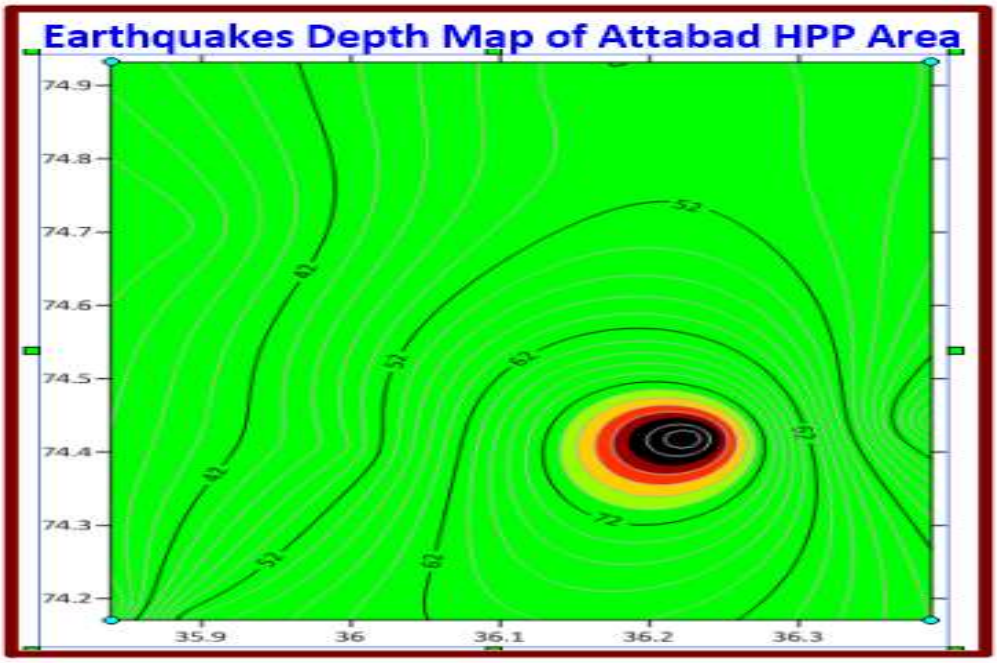

Figure 6-17 Earthquakes Focal Depth Contour Map of ALHPP Area. The Black Circle Shows the Dam / Weir Site and the Nearest Focal Depth to the Site is 72 km.

A composite seismic map showing both historical and instrumental earthquakes events for the past 1255 years (765 A.D. to 2020) is presented as Figure 6-18

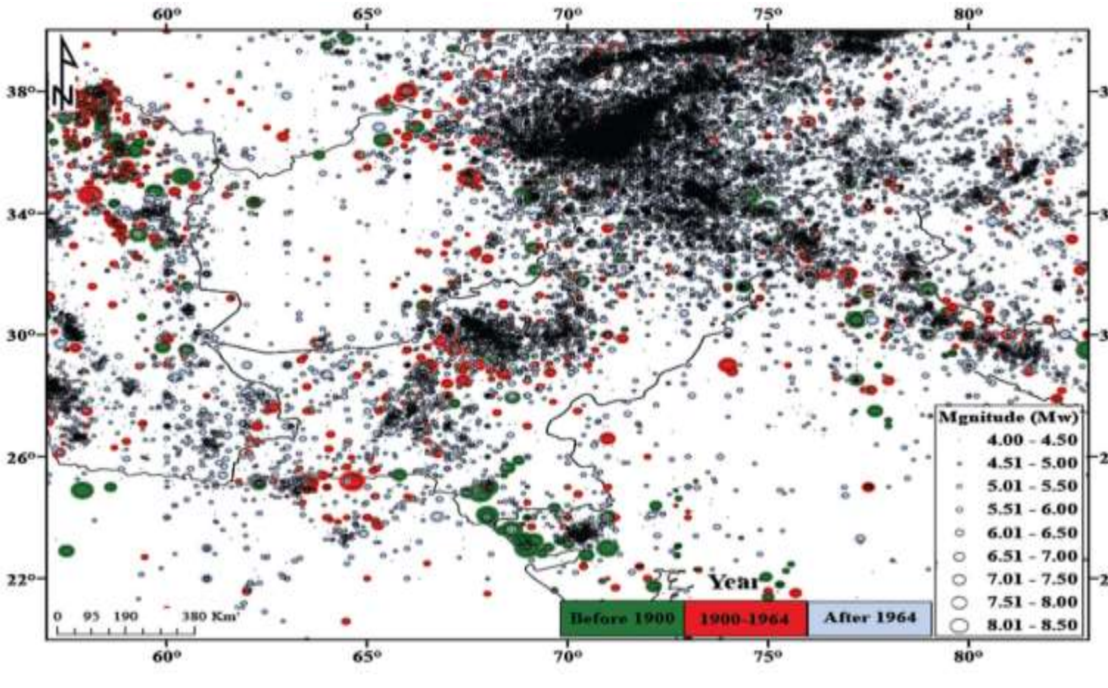

Figure 6-18 Seismic Map Showing Events with Magnitudes of the Past 1255 Years (765 A.D. to 2020).

6.4.1 Conversion of Magnitudes and Standard Deviation

The earthquakes reporting agencies have given a variety of magnitudes viz: Body-wave magnitude (m_b), Surface-wave magnitude (M_S), Richter/Local magnitude (M_L) or Duration-magnitude (M_D) etc. Since ground motion prediction equations are based on magnitude of given type, a single type must be selected. For data to be used in seismic hazard analysis, all these different magnitudes were converted to moment magnitude (M_W) by the following equations.

Conversion from M_S and m_b to M_W was achieved through latest equation suggested by Scordilis (2006):

$M_W = 0.67\ M_S + 2.07$ for $3.0 \leq M_S \leq 6.1$

$M_W = 0.99\ M_S + 0.08$ for $6.2 \leq M_S \leq 8.2$

$M_W = 0.85\ m_b + 1.03$ for $3.5 \leq m_b \leq 6.2$

For M_L up to 5.7, the value of M_L was taken equal to M_W as suggested by Idriss (1985) and supported by operators of local networks in Pakistan. Conversion of M_L to M_W beyond magnitude 5.7 was done by using the following equations suggested by Ambraseys and Bommer (1990) and Ambraseys and Bilham (2003):

$0.82\ (ML) – 0.58\ (MS) = 1.20$

$\text{Log Mo} = 19.09 + MS$ for $MS < 6.2$

$\text{Log Mo} = 15.94 + 1.5\ MS$ for $MS > 6.2$

$MW = (2/3)\ \text{Log}\ (Mo) – 10.73$

Where m_b is body–wave magnitude, M_S is surface-wave magnitude, M_L is local magnitude, All available types of magnitudes in the catalogue were converted into a uniform magnitude-scale i.e. M_W (Moment magnitude). Observed dependence of σ (standard deviations) on Moment Magnitudes is given is Figure 19. The earthquakes reporting agencies have given a variety of magnitudes viz: Body-wave magnitude (m_b), Surface-wave magnitude (M_S), Richter/Local magnitude (M_L) or Duration-magnitude (M_D) etc. Since ground motion prediction equations are based on magnitude of given type, a single type must be selected. For data to be used in seismic hazard analysis, all these different magnitudes were converted to moment magnitude (M_W) by the following equations.

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$M_W = 0.85\ m_b + 1.03$ for $3.5 \leq m_b \leq 6.2$

For M_L up to 5.7, the value of M_L was taken equal to M_W as suggested by Idriss (1985) and supported by operators of local networks in Pakistan. Conversion of M_L to M_W beyond magnitude 5.7 was done by using the following equations suggested by Ambraseys and Bommer (1990) and Ambraseys and Bilham (2003):

$0.82\ (ML) – 0.58\ (MS) = 1.20$

$\text{Log Mo} = 19.09 + MS$ for $MS < 6.2$

Log Mo = 15.94 + 1.5 MS for MS > 6.2

MW = (2/3) Log (Mo) – 10.73

Where m_b is body–wave magnitude, M_S is surface-wave magnitude, M_L is local magnitude, All available types of magnitudes in the catalogue were converted into a uniform magnitude-scale i.e. M_W (Moment magnitude). Observed dependence of б (standard deviations) on Moment Magnitudes is given is Figure 6-19

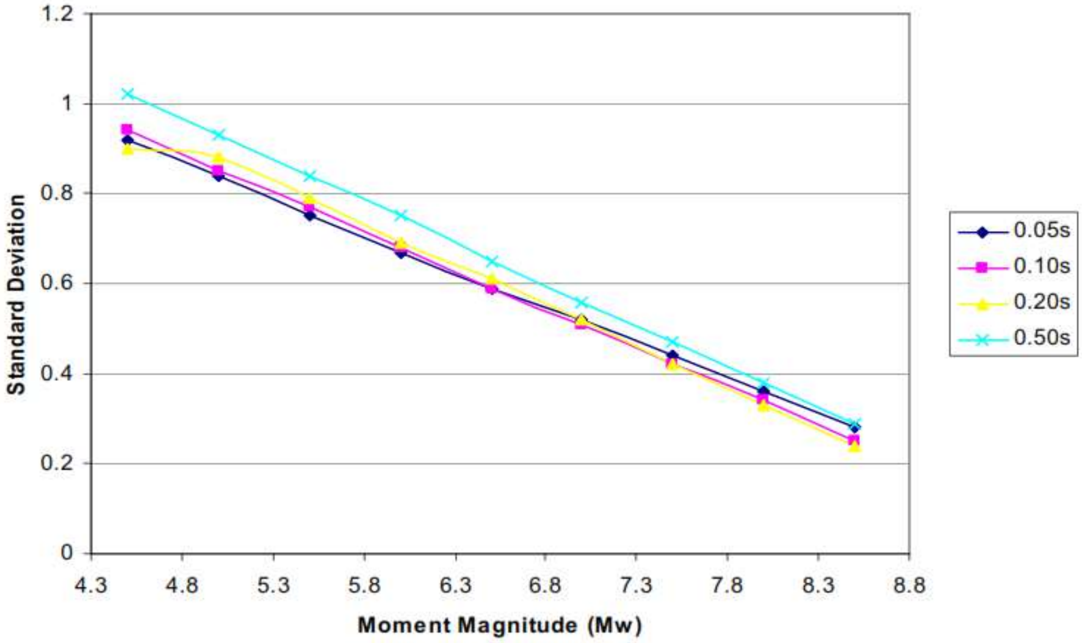

Figure 6-19 Standard Deviations (б) Vs Moment Magnitudes (Mw).

6.4.2 Kashmir Earthquake (M 7.6) of October 08, 2005 and the New Scenario

The powerful earthquake with a magnitude of M_W =7.6 that struck the northern part of Pakistan and Kashmir on October 08, 2005, caused widespread damage in Azad Kashmir and adjoining areas of KPK. This prompted for consideration of re-activation of previously perceived dormant faults segments as active fault segments in the new scenario.

The epicenter of this earthquake was located northeast of Muzaffarabad. This earthquake was felt for several minutes in Pakistan, northern India, and Afghanistan. The heaviest damage was recorded in the towns of Balakot, Batal, and Batagram in KPK and Muzaffarabad, Bagh and Rawalakot in Azad Kashmir where the entire population was badly affected. Building collapse were also reported in Muzaffarabad, Mansehra, Abbottabad, and Islamabad. Severe cracks were observed in many high-rise buildings in Islamabad too. The death toll due to this earthquake exceeded 80,000 people and millions were rendered homeless due to collapse of houses. The earthquake was followed by a series of more than thousand aftershocks, hundreds of them exceeding magnitude M 4.0. This earthquake was caused by the movement due to rupture along a thrust fault named the "Balakot-Bagh Thrust" (BBT) which is a northern most branch of the MBT like Riasi Thrust, a main branch of the MBT in Kashmir as shown in Figure 6-20. Ground ruptures and fresh landslides have been observed along this fault at many places near Muzaffarabad and Balakot.

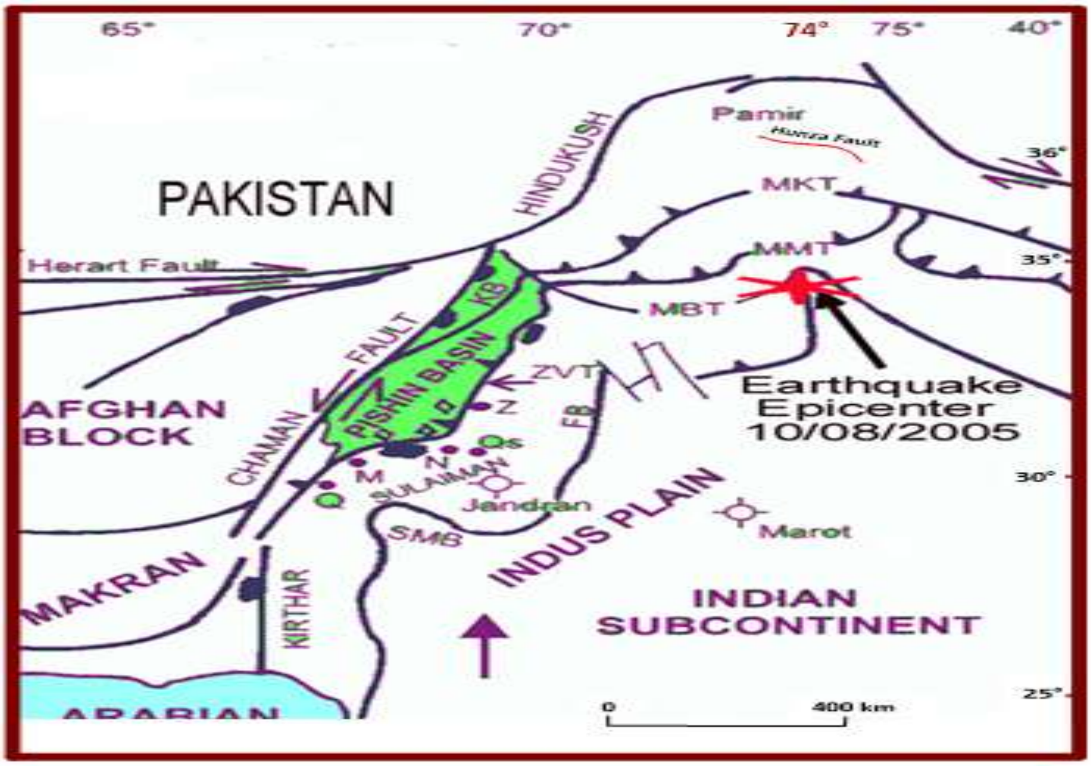

Figure 6-20 Earthquake Epicenter of Kashmir Earthquake of October 8, 2005.

Thus, the Kashmir earthquake of 8th October, 2005 has changed the scenario of seismic design in Pakistan and prompted for design review of Neelum Jhelum Hydropower Project where MBT and Panjal Thrust are crossing the dam area. These two faults were previously considered as dormant faults. After the earthquake of 8th October, 2005, these two faults were considered as active faults and seismic design parameters were reviewed and changed to the much safer side resulting in massive cost overruns. The new scenario also prompted to revise Building Code of Pakistan which was revised and updated in 2007 accordingly thereby enhancing the design parameters in the new scenario. Hence, previously adopted design codes and parameters were considered as under estimated and began to enhance the safety factors in seismic design for buildings and ordinary structures in Pakistan. In the wake of the new scenario seismic design parameters of dams and water retaining structures are also being given due importance towards conservative sides.

Since the revision of Next Generation Attenuation relations by Pacific Earthquakes Engineering Research Center (PEER) of USA in 2014, seismic safety factors are being given due considerations as per ICOLD's Revised Guidelines given in Bulletin 148 (2016).

The present analysis is in line with these national and global developments. In the present seismic hazard analysis, the latest ground motion prediction equations known as NGA West 2 Attenuation Relations (2014) have been used and the latest version of R-CRISIS software Ver 20.1.1. and Ez-Frisk Ver 7.65 have been used for seismic hazard analysis of ALHPP.

6.5 INDENTIFICATION OF SEISMIC SOURCES

Based on the understanding of the analysis of seismicity, tectonic setting, major faults of the area and area-seismic related seismogenic features within 200 km radial distance of the Project Site, the area seismic sources for the Project include Karakorum Seismic Zone, Nanga Parbat-Haramosh Seismic Zone, Western Himalayas Seismic Zone, Hindukush Seismic Zone, Kashmir Himalayas Seismic Zone and Kohistan Seismic Zone.

The significant point seismic sources (faults) capable of generating earthquakes for ALHPP, include;

a. Hunza Fault (Thrust Fault)

b. Main Karakoram Thrust (MKT),

c. Main Mantle Thrust (MMT)

The area seismic sources within a radial distance of 200km include

Quantitative features of these controlling faults are given in tabulated form in Table 1.

Table 6-1 The Controlling Faults with Quantitative Features (input values of DSHA)

Controlling Faults	Fault Type	Fault Rupture Length (km)	Distance (km)	Maximum Magnitude Potential	
				As per Catalogue data	Conservatively Assigned
Hunza Fault	Thrust	5 inferred	1.4	6.1	6.7
MKT	Thrust	200	32	7.0	7.6
MMT	Thrust	260	71.69	6.9	7.6

Brief description of the seismogenic sources for the Project is given below,

6.5.1 HUNZA FAULT (HF)

The upper HF is considered as a splay fault of MKT (Pitcher et al. (2008) and as the northern limit of MKT (Desio 1979). It is present at the Project Site at a distance of about 1.4 km from the proposed intake / diversion tunnel of ALHPP (Figure 2). It is thrust type fault. Associated with HF, there are many small local faults with unknown fault parameters such as rupture length etc. in the area. Presence of HF and many minor local faults along with some neotectonic features as reported by site geological mapping indicate that the fault is active. However, analysis of tele-seismic data for the last 100 years shows that the Project Area has low concentration of earthquake events with seismicity class of low to moderate seismicity and there has been no earthquake activity greater than magnitude 5.2 as per analysis of composite catalogue.

6.5.2 MAIN KARAKORUM THRUST (MKT)

The MKT is a low angle mega-shear thrust fault with strike slip components as segmented regime at places, which passes through Chalt (near Hunza) on eastern side and extended on western side through Ishkuman and Yasin valleys into Baltistan Area in Hasupa Shigar valley, Machelu in Shyok valley and and Shishi valley. It encircles the Island Arc Zone on the northern side in Chitral Area. Its general trend swings between E and E-NE and dips towards the north at low to medium angle.

MKT is located at a distance of 32 km from ALHPP towards south (Figure 6-2). Some segments of this 700km-long thrust fault is seismically active.

6.5.3 MAIN MANTLE THRUST (MMT)

The MMT, which is aligned with the Nanga Parbat-Haramosh Massif (NPHF) tectonically, spans over an area of about 400 km through Diamer, Kohistan, and Bajour, before entering Afghanistan. The general trend of MMT is NE-SW. It is located along the contact of the mafic/calc-alkaline meta igneous rocks and the meta-sediments belonging to the Indo-Pakistan continental mass. Along this megashear near Jijal village on Indus River (right bank), the igneous rocks have overthrusted the meta-sediments to the south over a 10-15 km wide zone. The thrust also manifests as the broad high topography of Kohistan relative to the Hazara to the south. In addition, numerous auxiliary fractures were developed and across the thrust frequent brecciation and mylonitization are also present along the contact. Some segments of MMT is seismically active. Due to its seismic activity and tectonic impacts, this fault has also been considered in seismic hazard assessment of ALHPP.

The last limit of MMT nearest to the Project Area is located at a distance of 71.69 Km from ALHPP (Figure 6-2).

The above mentioned faults have been used in DSHA approach. However, in PSHA approach, area seismic sources have been used in the present study, being more reliable as compared to point sources.

The used area seismic sources include Karakorum Seismic Zone, Nanga Parbat-Haramosh Seismic Zone, Western Himalayas Seismic Zone, Hindukush Seismic Zone, Kohistan Seismic Zone and Kashmir Himalayas Seismic Zone.

6.6 SEISMOTECTONICS

From the available tectonic and seismic data, seismo-tectonic analysis of ALHPP was done. Seismo-tectonic map of ALHPP and Northern Pakistan showing the seismic concentrations over active seismic sources have been developed and are presented as Figures 6-21 and 6-22.

Figure 6-21 Seismo-Tectonic Map of the Project Area. Rectangle Shows the Project Area.

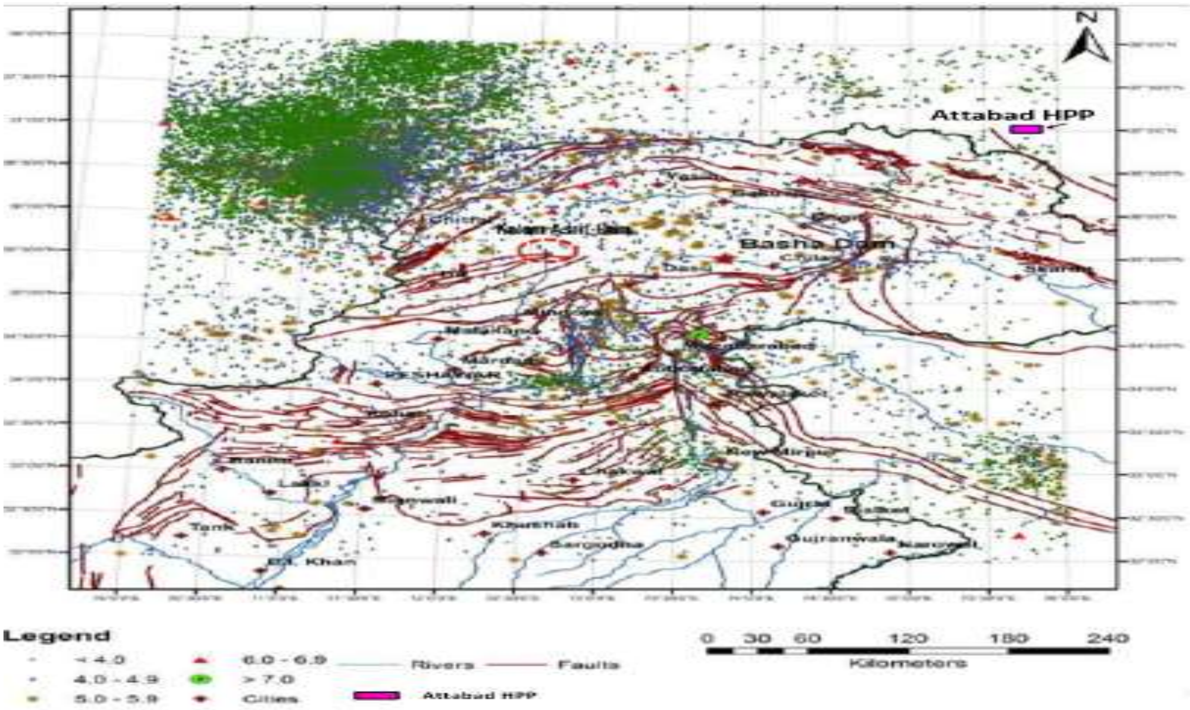

Figure 6-22 Seismo-Tectonic Map of Northern Pakistan Showing Project Area.

6.7 PROBABILISTIC SEISMIC HAZARD ASSESSMENT (PSHA)

6.7.1 PSHA Methodology

The principle of the analysis, first developed by Cornell (1968) and later refined by various researchers, is to evaluate at the site of interest the probability of exceedance of a ground motion parameter (e.g. acceleration) due to the occurrence of a strong event around the site. This approach combines the probability of exceedance of the earthquake size (recurrence relationship), and probability on the distance from the epicenter to the site. Each seismic source zone is divided into elementary source zones at a certain distance from the site. Integration is carried out within each zone by summing the effects of the various elementary source zones taking into account the attenuation effect with distance. Total hazard is finally obtained by adding the influence of various sources. The results are expressed in terms of a ground motion parameter associated with return period (return period is the inverse of the annual frequency of exceedance of a given level of ground motion). The seismic hazard model used in the present analysis was developed based on both area source as well as fault sources in the light of findings of the seismotectonic synthesis. Each seismic source zone is defined as a zone with homogenous seismic and tectonic features, inferred from geological, tectonic and seismic data. These zones are first defined, and then a maximum earthquake and an earthquake recurrence equation are elaborated for each of these seismic source zones. The present work is the first of its kind in which both NGA West 1 and NGA West 2 ground motions equations have been used for seismic hazard assessment of ALHPP.

The seismic parameters attached to the various seismic source zones are: a recurrence relationship relating the number of events for a specific period of time to the magnitude; the maximum earthquake giving an upper bound of potential magnitude in the zone; and an attenuation relationship representing the decrease of acceleration with distance. The PSHA requires a detailed analysis of distribution of observed seismic data to the seismic sources, determination of b-value and activity rate of each seismic source and assigning maximum magnitude potential to each seismic source.

6.7.2 Earthquake Recurrence Model

A general equation that describes earthquake recurrence may be expressed as follows:

$$N(m) = f(m, t) \qquad (1)$$

Where N (m) is the number of earthquakes with magnitude equal to or greater than m, and t is time period.

The simplest form of equation (1) that has been used in most engineering applications is the well-known Richter's law which states that the cumulated number of earthquakes occurred in a given period of time can be approximated by the relationship

$$\text{Log } N(m) = a - b\,m \qquad (2)$$

Equation (2) assumes spatial and temporal independence of all earthquakes, i.e. it has the properties of a Poisson model. Coefficients 'a' and 'b' can be derived from seismic data related to the source of interest. Coefficient 'a' is related to the total number of events occurred in the source zone and depends on its area, while coefficient 'b' represents the coefficient of proportionality between log N (m) and the magnitude.

The composite catalogue of earthquakes prepared for the ALHPP Area provided the necessary database for the computation of b-value for each seismic area source zone. The composite earthquake list contains limited number of earthquakes prior to 1960 and only few of these earthquakes have been assigned magnitude values. Due to installation of WWSSN, the earthquake recording in this region improved and a better and complete recording of earthquake data are available after 1960. The completeness analysis of the overall data for the region showed that earthquake data up to magnitude 4.0 is complete after 1960.The converted moment magnitude for the period between 1961 and 2020 was therefore used in the PSHA after excluding the aftershocks. Magnitude-frequency curves were made for each seismic area source and presented as Figure-23. The b-value for each seismic area source zone was calculated using linear regression through least square method. The minimum magnitude for each area source zone was selected from the magnitude-frequency curve based on completeness checks suggested by Woeffner and Weimer (2005). The b–values, minimum magnitude and the activity rates for the seismic area source zones used in the PSHA are shown in Table 6-2.

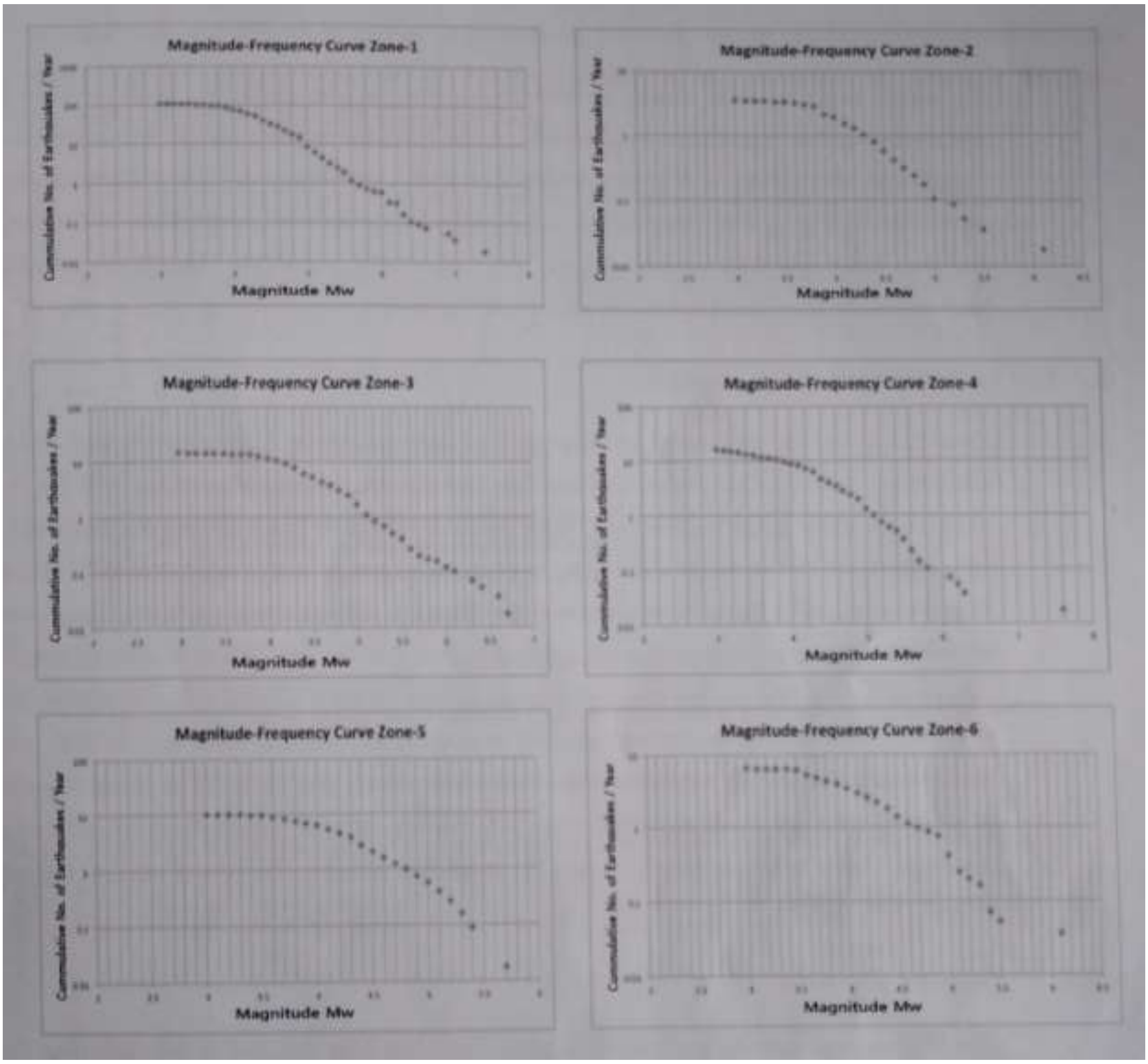

Figure 6-23 Magnitude-Frequency Curves of Seismic Sources.

6.7.3 Activity Rate of Seismic Sources

Activity rate of seismic sources have been worked out using Ez-Frisk software and the results of the analysis are shown in Figure 6-24.

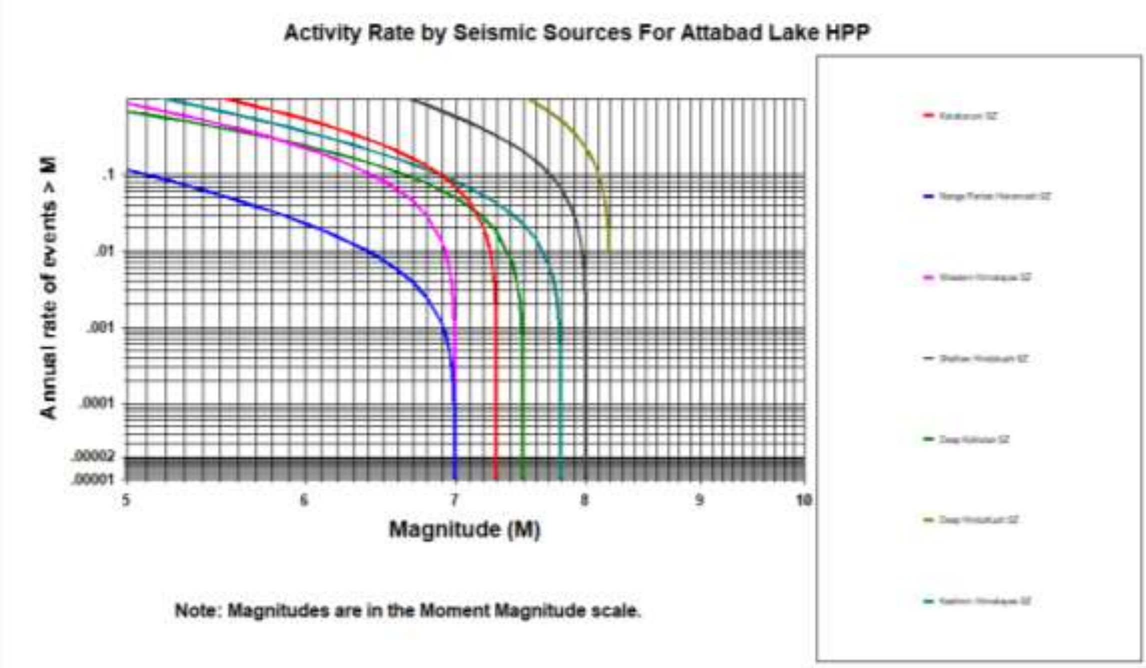

Figure 6-24 Activity Rate by Seismic Sources for ALHPP Area.

6.7.4 Maximum Magnitude

To each seismic source zone, a maximum magnitude potential was assigned based on the maximum observed seismicity in the historical seismic record and enhancing by 0.5 magnitude the maximum observed magnitude in the instrumental seismic record for that area seismic source zone and also determining the maximum magnitude of the longest active fault in the area using Well & Coppersmith equation (1994). The maximum potential magnitude used for each seismic area source zone is given in Table 6-1 and 6-2.

6.7.5 Ground Motion Prediction Equations

A number of ground motion prediction equations have been developed from strong motion database collected by USGS and Pacific Earthquake Engineering Research (PEER) Centre, USA. The latest ground motion prediction equations developed by PEER well known as Standard Five Sets of Next Generation Attenuations (NGA) West 2 have been used in the present analysis for ALHPP.

6.7.6 Seismic Sources Modeling

On the basis of tectonic, geologic and seismic characteristics, the following area source models within a radial distance of 200 km have been worked out and the same have been used as input parameters in PSHA for ALHPP.

Table 6-2 Seismic Source Zones Parameters for PSHA

Source Zone No.	Seismic Source Zone Name	Minimum Magnitude Mw	Activity Rate / Year	b-Value	Maximum Magnitude Mw
1	Karakorum Seismic Zone	4.0	1.929	1.120	7.3
2	Nanga Parbat Seismic Zone	4.2	1.112	1.101	7.0
3	Western Himayan Seismic Zone	4.1	5.339	1.44	7.0
4	Hindukush Seismic Zone	4.2	59.107	1.20	8.0
5	Kashmir Himalaya SZ	4.2	7.143	1.13	7.8
6	Kohistan SZ	4.1	10.500	1.07	7.5

Each of these area sources were assigned a maximum magnitude based on recorded seismicity and potential of the faults within the zone and a minimum magnitude based on threshold magnitude observed in the magnitude-frequency curve for the source zones (Figure - 23). As the shallow earthquakes are of more concern to seismic hazard, the minimum depth of the earthquakes is taken as 5 km for all area sources.

The source zone parameters used in deterministic approach is given in Table 6 - 1 and seismic sources parameters for PSHA for the ALHPP are presented in Table 6 - 2.

As the description of all these area seismic sources is found in already published literatures, therefore, their repetition has been avoided here for the sack of conciseness and brevity of the report.

6.8 RESULTS OF PROBABILISTIC HAZARD ANALYSIS

Both PSHA and DSHA were carried out using EZ-FRISK software Version 7.65 developed by Risk Engineering Inc. USA. The latest version of R-CRISIS Software Version 21.1.1 developed by PEER, USA was also used during the current study. The purpose of using both softwares was to cross check the validation comparing the quality of the seismic hazard analysis of the two software for the Project. During the study it was found that Ez-Frisk software is more standardized as compared to R-CRISIS software in quality of analysis as well as the smart outputs of the analyzed results. Therefore, Ez-Frisk software has been preferred and used in the in the final analysis.

Important input parameters used in probabilistic approach are presented in Table - 2. It is assumed that weir/dam foundation will mainly be placed on gravelly soil (alluvium), therefore, the site condition was taken as gravelly soil with average shear wave velocity at 30 meters depth (V_{s30}) of 450 m/sec for soil site (alluvium) and 760 m/s for rock sites. The mean total hazard curve was obtained by giving equal weighting to all the Five NGA W2 Ground Motion Prediction Equations. The analyzed results of PSHA are presented in Figures 6-23 to 6-27.

The total hazard curve obtained for the Project Area is shown as Figure - 25 and the total mean Hazard Spectra showing combination of all used Ground Motion Prediction Equations for ALHPP is presented as Figure 6-26.

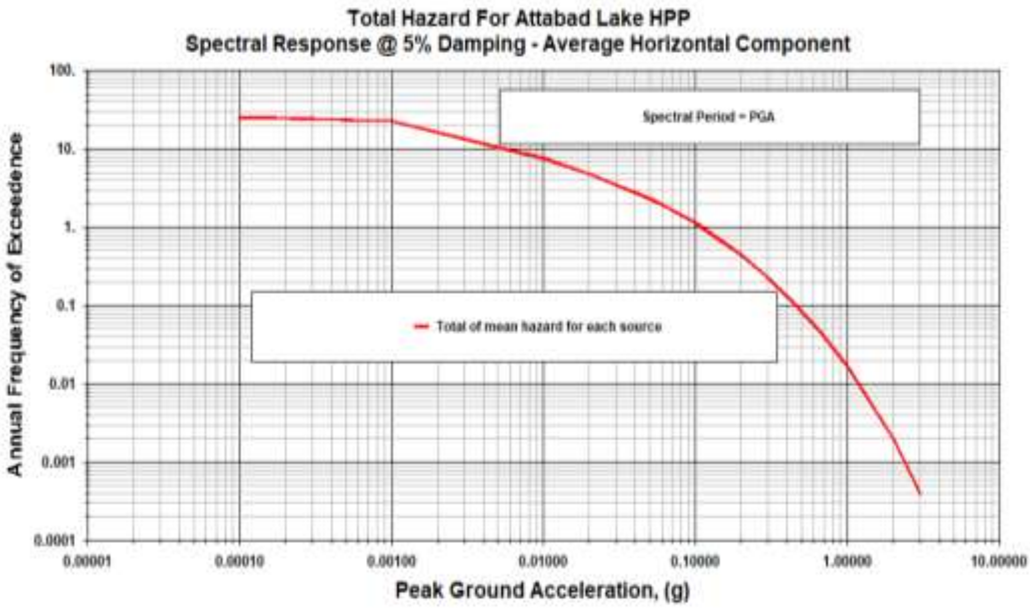

Figure 6-25 Total Hazard Curve for ALHPP

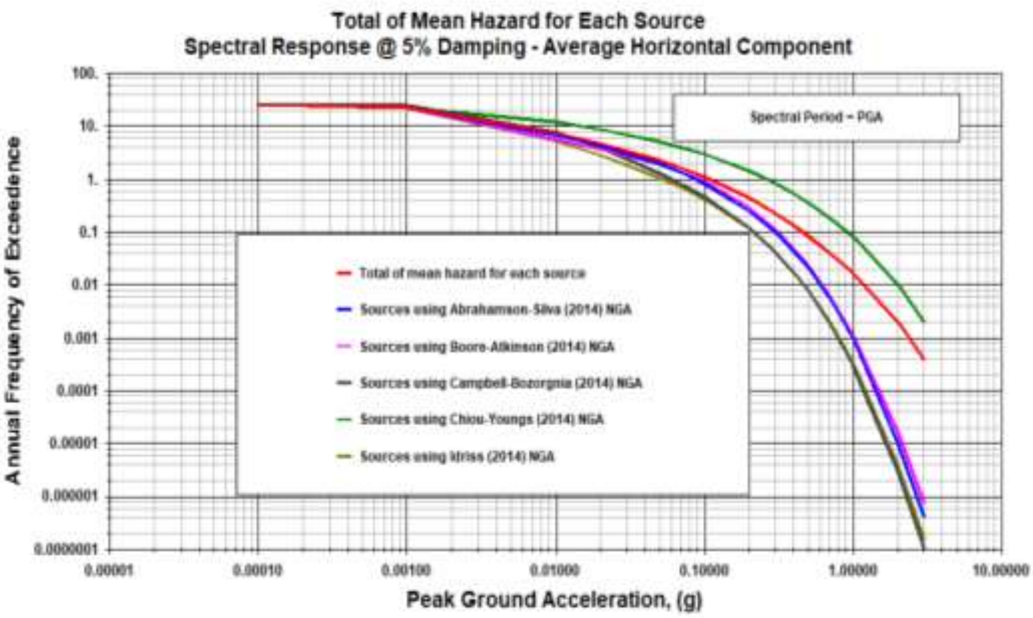

Figure 6-26 Total Hazard Spectra for ALHPP.

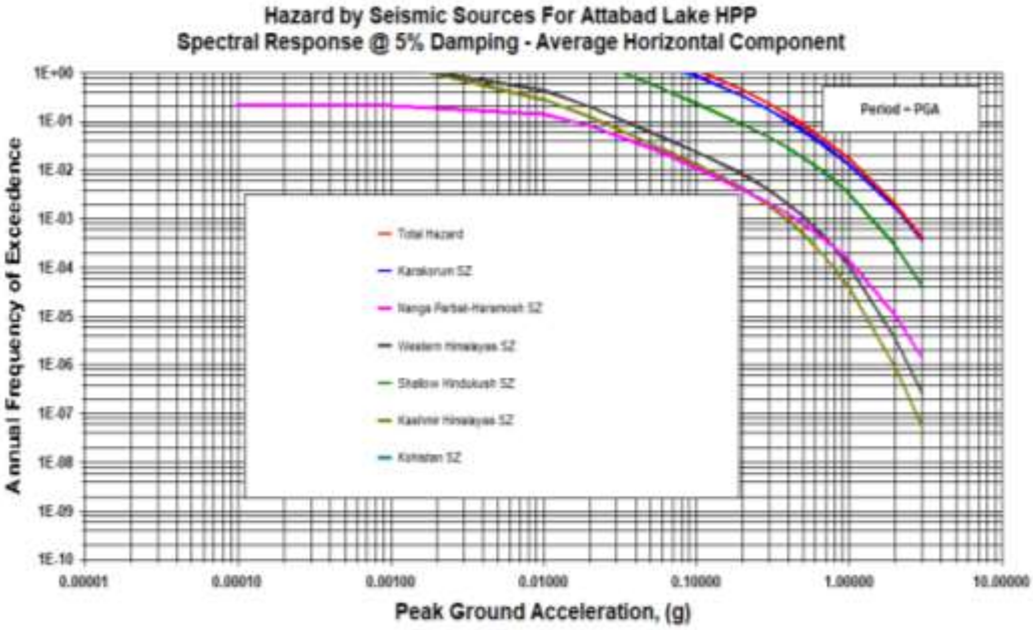

Figure 6-27 Hazard by Seismic Sources Contribution, Spectral Response @ 5% Damping for Average Horizontal Component for ALHPP..

6.9 DETERMINISTIC SEISMIC HAZARD ANALYSIS (DSHA)

The capability of the faults to generate earthquakes is ascertained by means of analysis of historical and instrumental seismic data and geological criteria such as rupture length – magnitude relationship or fault movement – magnitude relationship.

The main tectonic features around the Project Site within a radius of 200 km which could be controlling the maximum earthquake hazard are as follows:

1 Hunza Fault
2 Main Karakoram Thrust (MKT),
3 Main Mantle Thrust (MMT)

Empirical correlations have been developed between maximum potential of a fault and key fault parameters like rupture length, fault area, fault displacement and slip rate. Out of these fault parameters, only fault lengths are known with sufficient accuracy. For the faults around the ALHPP Site, the half rupture length of the faults has been taken for determination of maximum potential magnitude. The maximum earthquake magnitude (in moment magnitude M_W) of each of the fault was calculated using Wells & Coppersmith (1994) relationship between fault rupture length and magnitude and the input data given in Table - 1 has been used for deterministic approach.

Ground motion prediction equations developed under the Next Generation Attenuation (NGA) West 2 Project of PEER (Pacific Earthquake Engineering Research Center, University of California at Berkeley, USA) are used to obtain the median and median plus-one percentile levels of peak horizontal ground acceleration (PGA) in deterministic approach.

The NGA equations are developed using a large worldwide database of strong motion recording of earthquakes of magnitude 4-8 and distances ranging from 0-200 km in accordance with ICOLD Guidelines. The NGA equations are preferable over the older equations for the evaluation of seismic hazard particularly in the near field as these are based on a broad spectrum of data recorded in the near field. The same attenuation equations were used for the PSHA approach too.

For all the seismic sources, thrust rupture mechanism has been considered. It is assumed that dam foundation will mainly be placed on gravelly soil therefore the site condition for dam/weir was taken as gravelly soil with average shear wave velocity for top 30 meters (V_{s30}) of 760 m/sec. The depth to basement rocks (Z_{25}) is taken as 5 km. The PGA g values have been calculated using the latest Five sets of NGA West 2 Ground Motion Prediction Equations (GMPEs).

Input values in DSHA are given in Table - 1. The analyzed results obtained through DSHA are presented in Figures 6-28 to 6-30.

6.9.1 DETERMINISTIC RESPONSE SPECTRA

Deterministic response spectra for SEE at 50th percentile and 84th percentile levels are shown in Figure - 28 and Figure - 29 respectively.

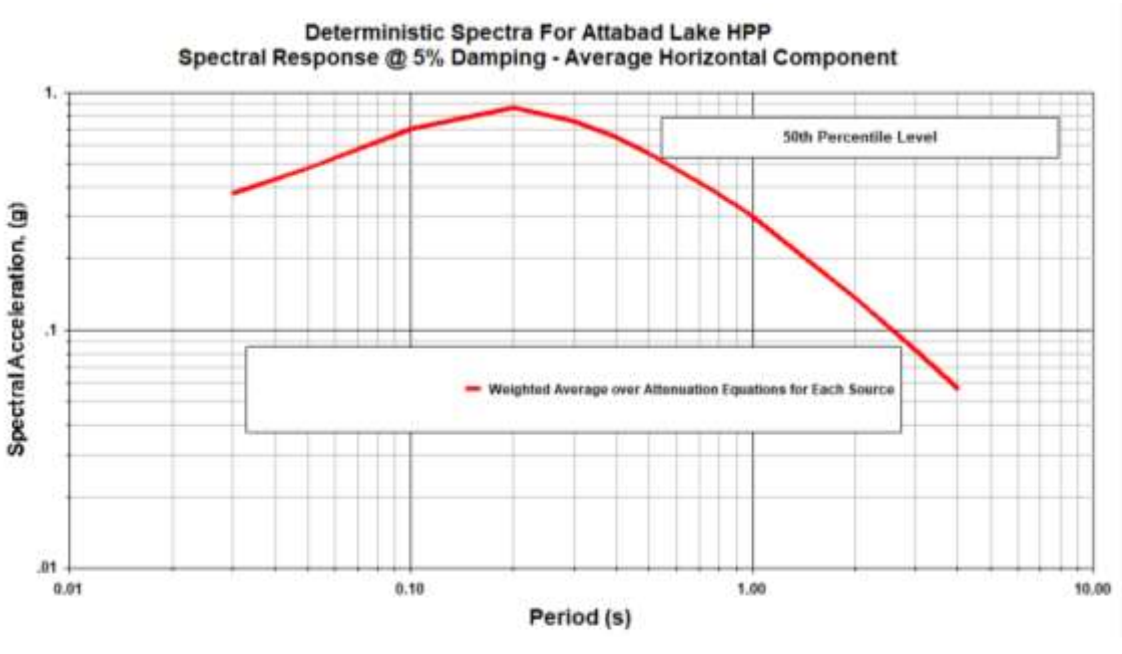

Figure 6-28 Deterministic Spectra at 50th Percentile Level

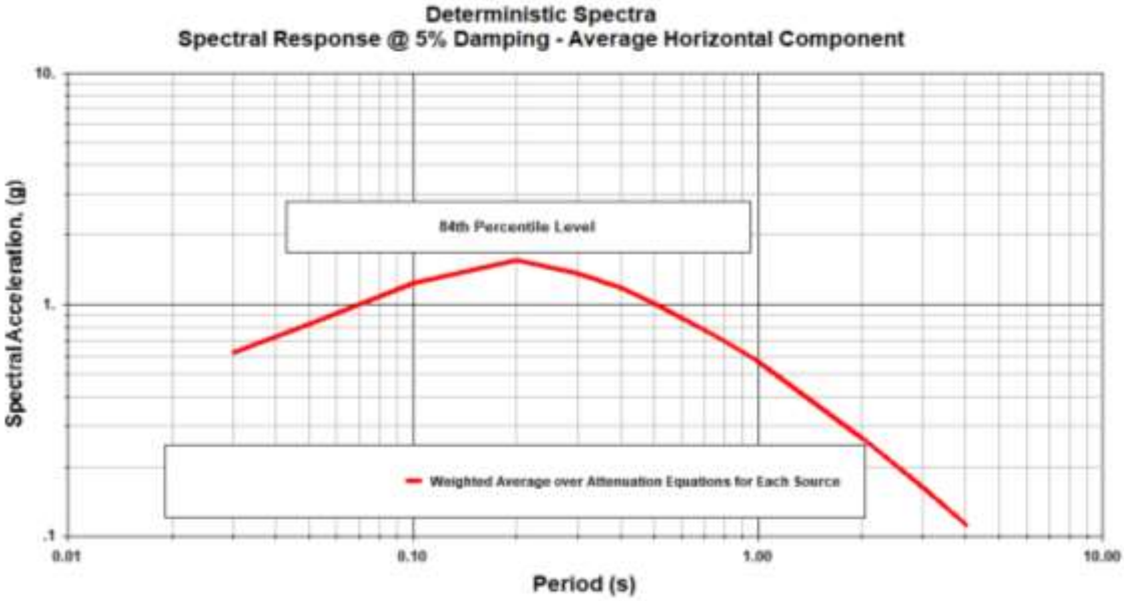

Figure 6-29 Deterministic Spectra at 84th Percentile Level.

6.9.2 Deterministic Pseudo Spectral Acceleration (PSA)

Pseudo spectral acceleration has been worked out using the latest version of R-CRISIS software. Pseudo spectral acceleration Vs time is given in Figure 6-30.

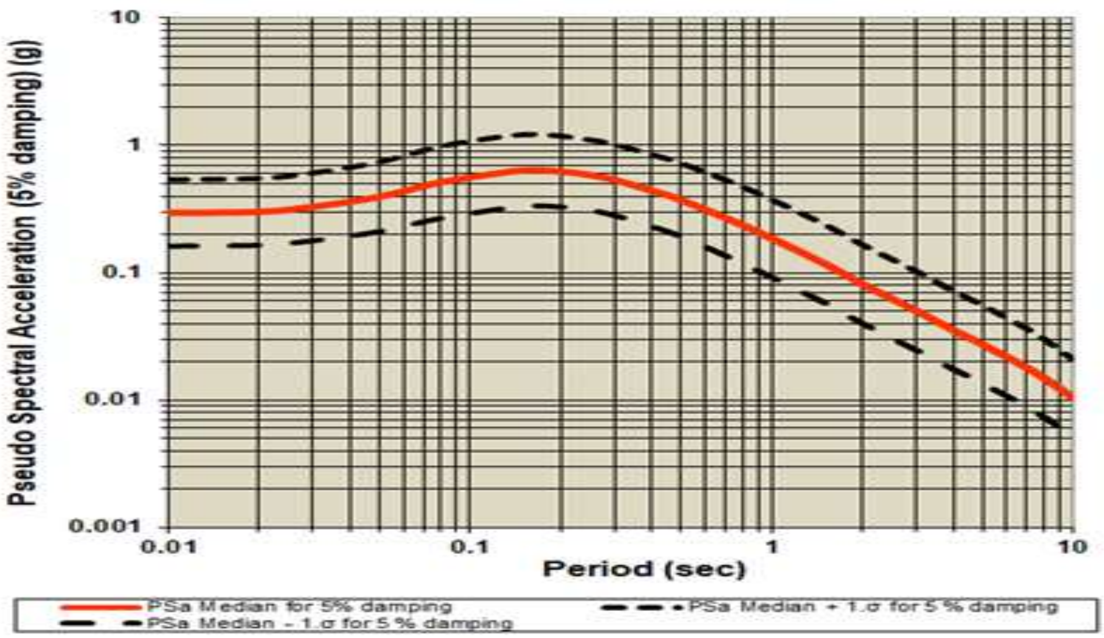

Figure 6-30 Deterministic Pseudo Spectral Acceleration (g) at 5% Damping.

6.10 SELECTION OF SEISMIC DESIGN PARAMETERS

6.10.1 Safety Evaluation Earthquake (SEE)

As per ICOLD guidelines, (2016) the SEE will produce the maximum level of ground motion for which the dam should be designed or analyzed. For dams whose failure would present a great social hazard, the SEE will normally be characterized by a level of motion equal to that expected at the dam site from the occurrence of deterministically evaluated MCE or of the probabilistically-evaluated SEE earthquake ground motion with a very long return period, for example 10,000 years for high consequence large dams. Depending on the circumstances (e.g. the importance of the dam, the consequences of a dam failure, it is recommended to design safety-critical elements such as the bottom outlet and/or spillway gates for the SEE. It will be required at least that there is no uncontrolled release of water when the dam is subjected to the seismic load imposed by the SEE.

As per the latest ICOLD Guidelines, for medium consequence dams, median value (50^{th} percentile level) is recommended whereas for high consequence dams, the SEE ground motion parameters should be estimated at median plus one (84^{th} percentile level) if developed by a deterministic approach and need not have a mean annual exceedance probability (AEP) smaller than 1/10,000 if developed by a probabilistic approach. For a particular project of importance such as hydropower project, optimum percentile level may be any optimum percentile level between 50^{th} percentile level to 95^{th} percentile level. For ALHPP, 66^{th} percentile level has been worked out and the same is recommended.

The worked out SEE for ALHPP are given in Figures 6-31.

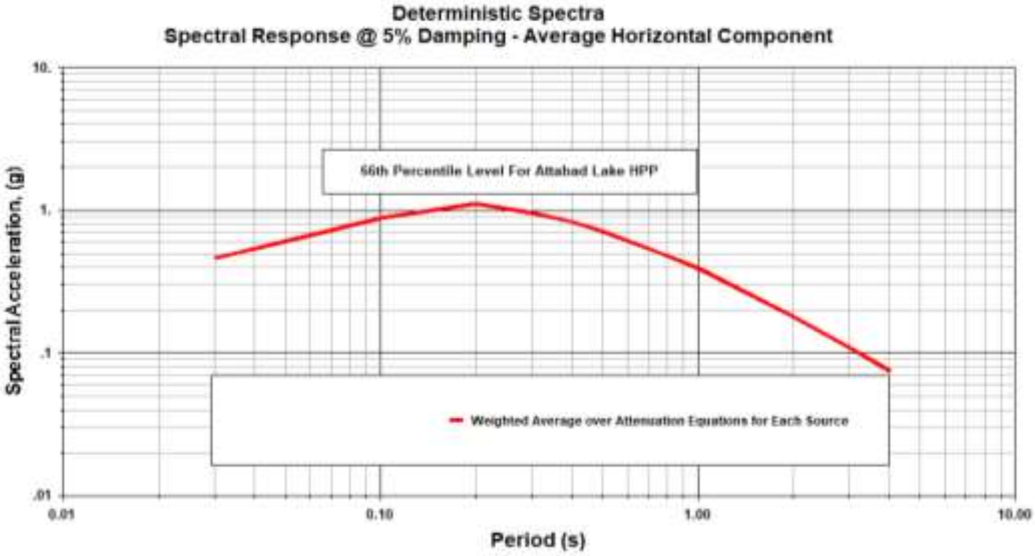

Figure 6 -31 Deterministic Spectra at 66th Percentile Level of SEE, Weighted Average over the Five NGA West 2 Equations for ALHPP.

6.10.2 Operating Basis Earthquake (OBE)

The OBE represents the level of ground motion at the dam site at which only minor damage is acceptable. In theory the OBE can be determined from an economic analysis, but this is not always feasible and, in many cases, it will be appropriate to choose a return period of about 145 years (i.e. a 50 % probability of not being exceeded in 100 years). The dam, appurtenant structures and equipment should remain functional and damage easily repairable, from the occurrence of earthquake shaking not exceeding the OBE.

Since the consequences of exceeding the OBE are normally economic, the circumstances in a particular case may justify use of a more severe or less severe event for the OBE. The resulting return period depends on prevailing conditions.

Because of the above definition, the OBE is the best determined by using probabilistic procedure. OBE ground motions are significantly lower than those for SEE.

6.10.3 Uniform Hazard Spectra (UHS)

Uniform hazard spectra for ALHPP for OBE (145 year return period), DBE (475 year and 2475 years return period) and SEE (10,000-years return period) are presented as Figure 6-32.

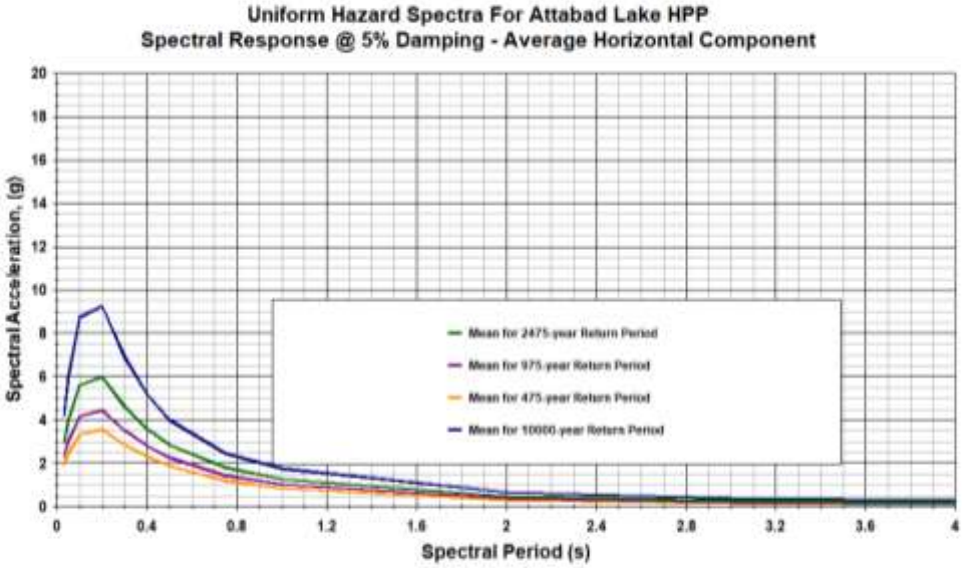

Figure 6-32 Uniform Hazard Spectra (UHS) for ALHPP.

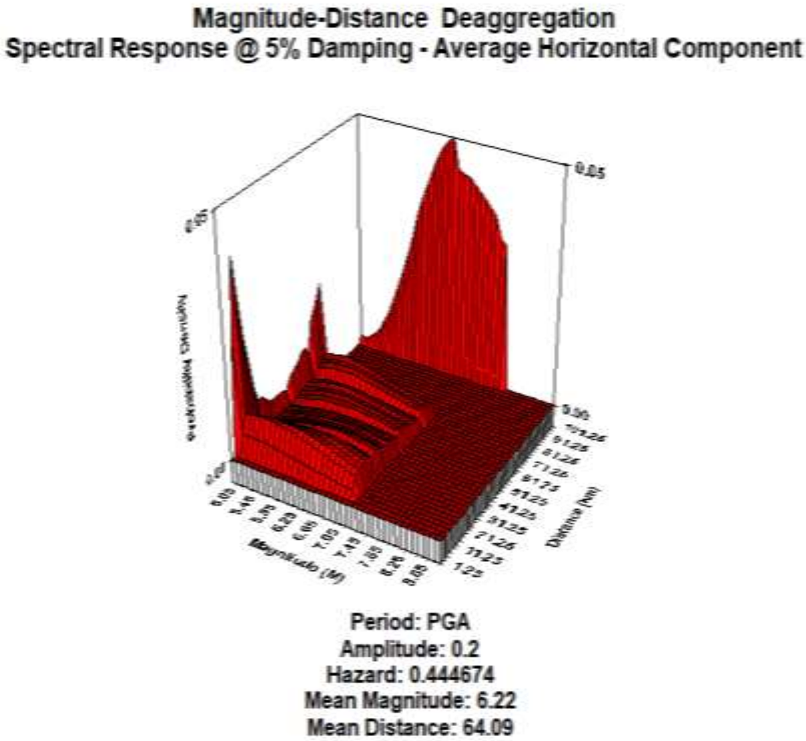

Figure 6-33 Deaggregation of Mean Hazard, Magnitude and Distance for SEE by PSHA for ALHPP

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7 CONCLUSION AND RECOMMENDATIONS

Based on the analysis results, the following earthquakes design parameters are concluded and recommended for ALHPP.

7.1 Operation Basis Earthquakes (OBE):

OBE at return period of 145 years is recommended as follows:

OBE Horizontal = 0.24 g

OBE Vertical = 0.17 g

7.2 Safety Evaluation Earthquakes (SEE):

For the design of dam / weir, the following PGA ‘g’ values for SEE are recommended:

SEE Horizontal = 0.44g

SEE Vertical = 0.29g

For the design of appurtinent structures including spillway etc. the following PGA ‘g’ values for SEE are recommended:

SEE Horizontal = 0.38g

SEE Vertical = 0.26g

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